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Air Pollution Emission Test. Volume I First Interim Report: Continuous Sulfur Dioxide Monitoring at Steam Generators

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The object of this study was to gather continous monitoring data for sulfur dioxide rates and removal efficiencies for flue gas desulfuization systems in support of possible revisions to the New Source Performance Standard. Four sites were monitored, two were later abandoned and yielded little information.

Analysis of the data indicated that: dampening of variable SO_2 emissions by scrubbing does occur; variability of outlet SO_2 emissions is substantial and caution should be used in developing emission standards "never to be exceeded;" and longer averaging times decrease the expected variability significantly.

-- Many tables included.

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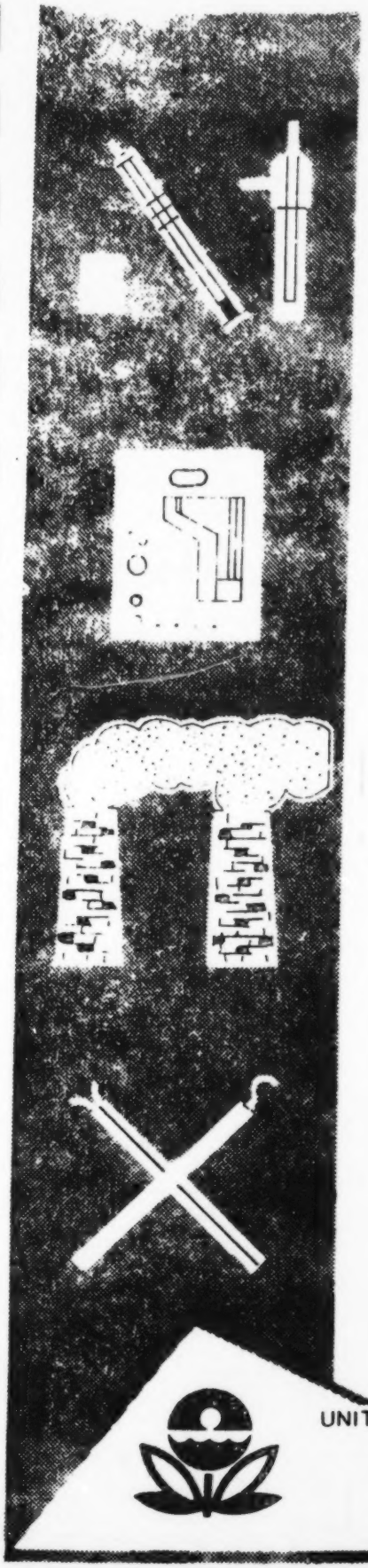

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VOLUME I: FIRST INTERIM REPORT:

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AT STEAM GENERATORS

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Office of Air Quality Planning and Standards
Emission Measurement Branch
Research Triangle Park, North Carolina

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AIR POLLUTION EMISSION TEST

Volume I: First Interim Report

Continuous Sulfur Dioxide
Monitoring at Steam Generators

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
Office of Air Quality Planning and Standards
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Research Triangle Park, North Carolina 27711

TABLE OF CONTENTS

List of Figures v
List of Tables vii
Summary of Results ix

Sections

I. INTRODUCTION AND DESCRIPTION OF TEST SITES 1
A. Introduction 1
B. Description of Test Sites 2
1. Cane Run Unit No. 4, Louisville Gas & Electric Co., Louisville, Ky. 2
2. Bruce Mansfield Unit No. 1, Pennsylvania Power Company 4
3. La Cygne No. 1, Kansas City Power and Light Co. 6
4. Eddystone Unit No. 1, Philadelphia Electric Co. 8

II. DATA GATHERING AND REDUCTION 11
A. Data Gathering Systems 11
1. Cane Run No. 4, Louisville Gas and Electric Company 11
2. Bruce Mansfield Unit 1, Pennsylvania Power Company 15
3. La Cygne Unit #1, Kansas City Power and Light Company 19
4. Eddystone No. 1, Philadelphia Electric Company 22
B. Data Reduction 24
C. Improvements and Research Needed 34

III. DATA ANALYSIS 37
A. Data Collection Interval Selection 37
B. Data Calculation Assumptions 40
C. Unusable Data 42
D. Usable Data and Statistical Analyses 42

IV. RECOMMENDATIONS AND CONCLUSIONS 61

LIST OF FIGURES

Figure		Page
I-1	Cane Run Station No. 4 Scrubbing Plant Gas Flow	3
I-2	Bruce Mansfield Station No. 1 Scrubbing System Gas Flow	5
I-3	La Cygne Station No. 1 Scrubbing Plant Gas Flow	7
I-4	Eddystone Station No. 1 Scrubbing Plant Gas Flow	9
II-1	Instrument System Schematic, Cane Run No. 4 Louisville Gas and Electric Company	12
II-2	Instrument System Schematic, Bruce Mansfield No. 1 Pennsylvania Power Company	16
II-3	Instrument System Schematic, La Cygne No. 1 Kansas City Power and Light Company	20
II-4	Instrument System Schematic, Eddystone No. 1 Philadelphia Electric Company	23
II-5	Sample Strip Chart Data	27
II-6	Sample Data Transcription Form	28
II-7	Sample Data Listing	30
II-8	Sample Average Listing and Statistical Summary	31
III-1	Inlet SO_2 Variation, Cane Run No. 4	38
III-2	Outlet SO_2 Variation, Cane Run No. 4	39
III-3	Probability Vs. Linear Inlet SO_2 Concentrations from Louisville Site	45
III-4	Probability Vs. Log Inlet SO_2 Concentrations	46
III-5	Probability Vs. Linear Outlet SO_2 Emissions from Louisville Site	47
III-6	Probability Vs. Log Outlet SO_2 Emissions	48
III-7	Probability Vs. Percent SO_2 Removal	52
III-8	Probability Vs. 100 Minus Percent SO_2 Removal	53
III-9	Louisville Data for 7 and 14 Day Averaging Periods	59

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LIST OF TABLES

Table		Page
III-1	Categorization of Data	43
III-2	Inlet SO_2 Emissions (24-Hr. Averaging Period)	49
III-3	Outlet SO_2 Statistics (24-Hr. Averaging Period)	51
III-4	SO_2 Removal Statistics (24-Hr. Averaging Period)	54
III-5	Variation in SO_2 Concentrations in $lb/10^6$ BTU (24-hour averages)	56
III-6	Cumulative Louisville Statistics Vs. Averaging Time	58

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SUMMARY OF RESULTS

A program was begun in May, 1977, to acquire SO_2 monitoring data in support of possible revisions to the New Source Performance Standard for fossil fuel fired steam generators, originally promulgated in December, 1971. Four sites were chosen for monitoring and the monitoring equipment was installed and tested. Data gathering began during July-September, 1977 at all sites and has continued through early 1978. Monitoring was discontinued at one site in October, 1977, with little useful data accumulated. Monitoring at another site was discontinued in December, 1977, after yielding only 85 days of data.

Data from the two remaining sites and data from another site obtained through other EPA programs were analyzed along with the 15 days data from one abandoned site. Mean SO_2 emissions ranged from 0.23 to 1.22 lb/Mbtu while mean SO_2 removal efficiencies ranged from 81.4 to 96.0 percent. Analyses of the variability indicate that:

- Dampening of variable SO_2 emissions by scrubbing does occur, especially with more reactive absorbents and good pH control.

- The variability of outlet SO_2 emissions is substantial, such that caution should be used in developing emission standards "never to be exceeded".

- Longer averaging times decrease the expected variability significantly.

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Insufficient data have been collected to examine the effects of long averaging period, i.e., 30 days or longer. The monitoring systems used to generate these data were not the type systems which would be recommended by EPA to gather data in such a study, rather the systems were simply adaptations of existing on-site SO_2 monitoring equipment to generate data at minimum delay and cost. As a result, the reliability of these systems during this study does not reflect the current capability of SO_2 monitors and data retrieval systems.

I. INTRODUCTION AND DESCRIPTION OF TEST SITES

A. INTRODUCTION

The objective of this program was to obtain continuous monitoring data for sulfur dioxide emission rates and removal efficiencies for flue gas desulfurization (FGD) systems. The primary use of this data was to perform statistical analyses on variations as a function of averaging time. These analyses, along with other information, were used to determine the appropriate averaging period for the revised standard of performance for new coal-fired steam generators.

Sulfur dioxide and oxygen concentrations were measured upstream and downstream of the FGD system using continuous instrumental monitors. Copies of boiler operation logs and FGD system operation logs were obtained to document process operating conditions during the monitoring periods.

All instruments were subjected to the appropriate performance specification test procedures[1] to assure the accuracy of the sulfur dioxide and oxygen measurements.

The monitoring program included testing at four steam generators. These were: (a) Cane Run Unit No. 4, Louisville Gas and Electric Co., Louisville, Kentucky, (b) Bruce Mansfield Unit No. 1, Pennsylvania Power Co., Shippingport, Pennsylvania, (c) La Cygne Unit No. 1, Kansas City Power and Light Co., La Cygne, Kansas,

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[1] Federal Register, Volume 40:194, October 6, 1975.

and (d) Eddystone Unit No. 1, Philadelphia Electric Company, Philadelphia, Pennsylvania.

Due to the magnitude of the program, four contractors were involved. Monsanto Research Corporation coordinated the overall program and processed the collected data. Midwest Research Institute, Scott Environmental Technology, Inc., and York Research Corporation had the responsibility of setting up monitoring equipment, performing the instrument performance specification tests, conducting routine calibrations and maintenance, and forwarding all data to Monsanto for processing.

B. DESCRIPTION OF TEST SITES

The four FGD systems serving steam generators included in this monitoring program are generally of different design and reactant types. These systems were designed several years ago (e.g., Bruce Mansfield designed in 1971) and, therefore, do not incorporate the latest design features expected at new installations. Additionally, the size and type of the steam generators are different. Further description of the individual sites is presented below.

1. Cane Run Unit No. 4, Louisville Gas and Electric Co., Louisville, Kentucky

Unit No. 4 at the Cane Run Station has an electric generating capacity of 181 megawatts. The boiler flue gases are passed through two parallel electrostatic precipitators for particulate removal and then to an FGD system designed by American Air Filter Corporation. The FGD system is divided into two modules (see Figure I-1). In each module, the flue gases first pass through a quench section for temperature reduction, then through a mobile-bed absorber equipped with sprays, then through a set of Chevron

CANE RUN STATION NO. 4 SCRUBBING PLANT GAS FLOW

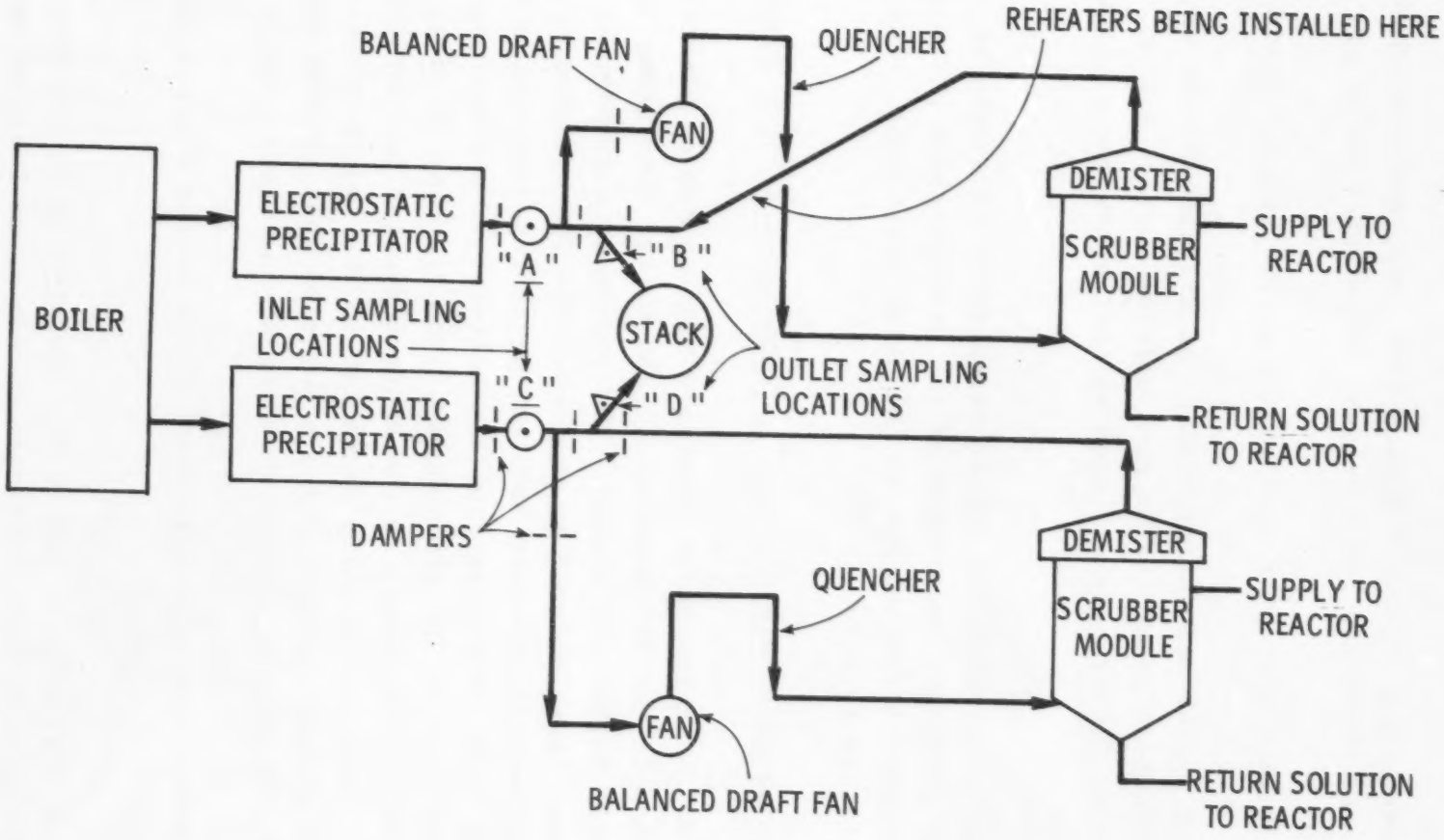

Figure I-1

demisters, also equipped with sprays, and then through a direct, oil-fired stack gas reheater near the stack breechings.

Carbide lime slurry is used as the sulfur removal reactant.

The FGD system was retrofitted to an existing boiler with an electrostatic precipitator particulates control system. The scrubbing modules are equipped so that stack gases may be by-passed.

The sulfur dioxide and oxygen measurement locations at the FGD system inlet are downstream of the precipitators while the outlet measurement locations are in the stack breechings. Monitoring was started in July, 1977.

2. Bruce Mansfield Unit No. 1, Pennsylvania Power Company

Unit No. 1 at the Bruce Mansfield Station has an electric generating capacity of 825 megawatts. The boiler flue gases are passed directly to the FGD system. The system is a tandem venturi-absorber type designed by Chemico. The FGD system is divided into six venturi-absorber modules, or trains (see Figure I-2). The boiler flue gases pass from the boiler into a common manifold for distribution to the six modules. The flue gas is first contacted with scrubbing slurry in the venturi section for particulates removal, then additionally contacted in the absorber section for sulfur dioxide removal. The gases then pass through direct oil-fired gas reheaters prior to entering the stack.

Thiosorbic lime slurry is used as the sulfur dioxide removal reactant.

The FGD system was designed and constructed at the same time as the boiler, so that the entire system is an integral unit. No provisions are included for direct bypass of flue gasses around

BRUCE MANSFIELD STATION NO.1 SCRUBBING SYSTEM GAS FLOW

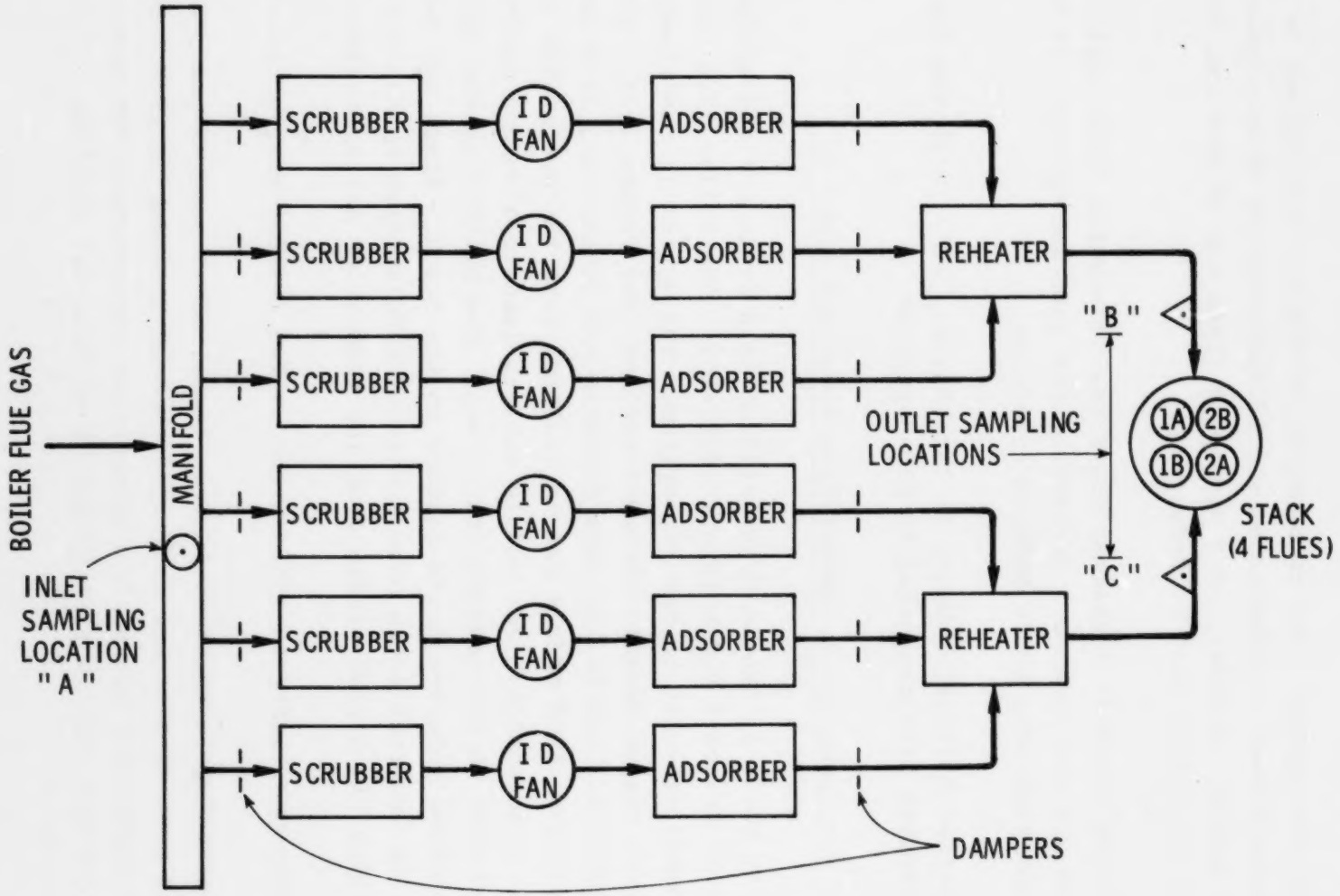

Figure I-2

the FGD system. Any combination of the six modules may be used under normal circumstances should difficulties be encountered in a module. However, if a module is taken out of service, the boiler output must be reduced.

One of the Unit 1 chimney flues was undergoing liner repairs during the test period. Therefore, the unit was operated at half-load with only three modules available.

Partial monitoring began in late August, 1977, with the first complete data beginning in mid-September.

3. La Cygne No. 1, Kansas City Power and Light Co.

Unit No. 1 at the La Cygne station is a cyclone-fired boiler which drives a 820 megawatt generator. The boiler flue gases are passed directly to the FGD system. The system is comprised of eight tandem venturi-absorber modules (see Figure I-3). The FGD system and the boiler were designed and constructed as a complete package. Each module can be isolated from the system for individual maintenance. The module outlets lead to a common manifold and then to six induced draft fans. The outlets of the fans are combined into two ducts leading to the stack. Stack gas reheat is by indirect steam heat exchange, supplemented by hot air addition via a side stream from the combustion air preheaters.

Limestone slurry is used as the sulfur dioxide removal reactant.

Monitoring instrumentation was installed in early August, 1977, and partial data was collected through November 5, 1977. Because of instrument operation difficulties and atypical FGD system operation, only a limited amount of data was obtained.

LA CYGNE STATION NO. 1 SCRUBBING PLANT GAS FLOW

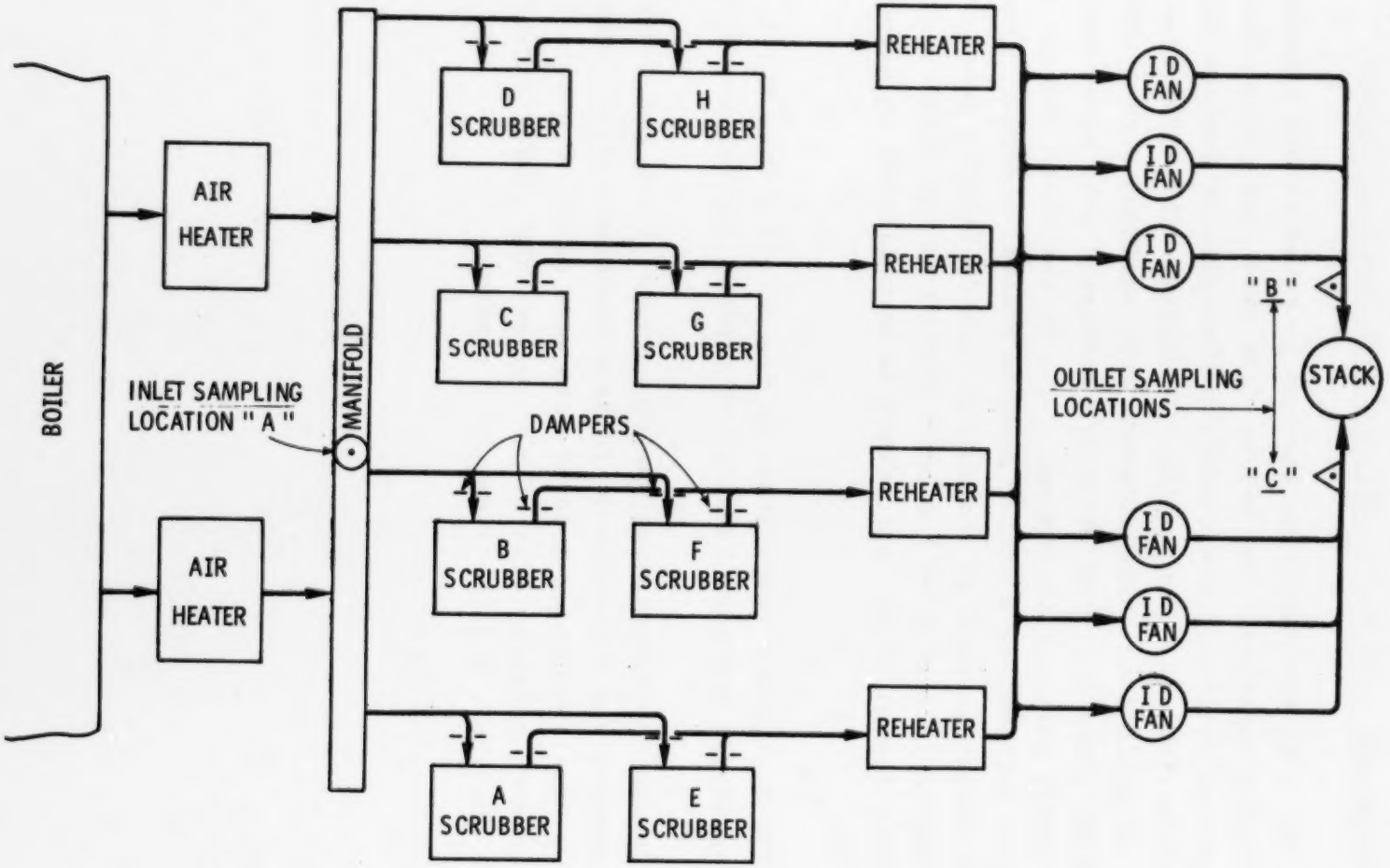

Figure I-3

4. Eddystone Unit No. 1, Philadelphia Electric Company

Unit No. 1 at the Eddystone station is rated at 325 megawatts generating capacity. The boiler flue gases are passed through a mechanical collector/electrostatic precipitator section for particulates removal, then to the FGD system. The total flue gas flow is split into three streams, each equipped with a venturi scrubber where the flue gases are contacted with river water for additional particulate removal. One of the three venturi scrubbers is followed by a sulfur dioxide removal absorber. Magnesium oxide slurry is used as the sulfur dioxide removal reactant. Testing in this program has been limited to the total venturi-absorber train. Stack gas reheat is accomplished by direct oil firing.

The FGD system was retrofitted to the existing Unit No. 1. Flue gas bypass is provided in order to protect the boiler on Unit 1.

Monitoring instrumentation was operational since mid-August, 1977, and testing was discontinued in late December, 1977. However, only a small number of days of data were obtained due to limited concurrent operating time of the boiler, the sulfur dioxide removal absorber, and the instrument systems.

EDDYSTONE STATION NO. 1 SCRUBBING PLANT GAS FLOW

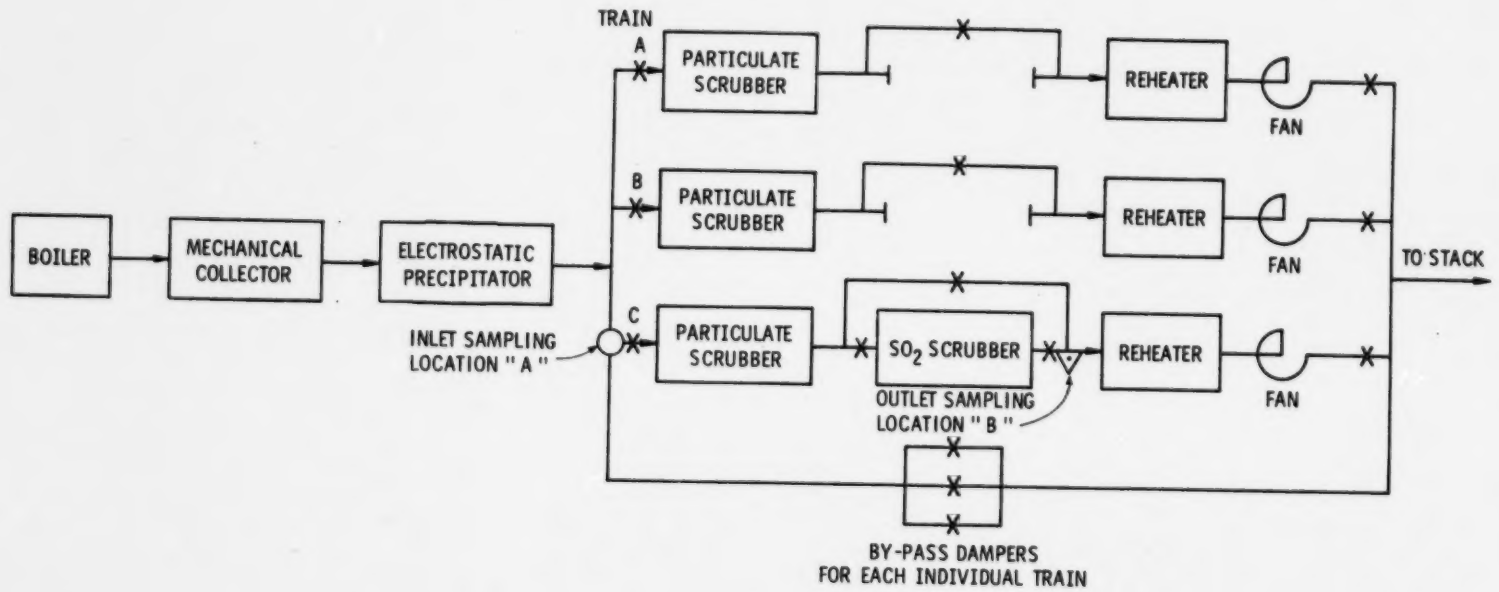

Figure I-4

II. DATA GATHERING AND REDUCTION

A. DATA GATHERING SYSTEMS

The sulfur dioxide monitoring equipment at all test locations were DuPont Model 460 Photometric analyzers[2]. The basic instrument configuration varied from site to site and is discussed below. The oxygen monitoring equipment varied from site to site; however, the basic detection principle was the same. The oxygen measurement equipment is described in detail in the site descriptions below. Continuous instrumental moisture measurements were not performed. The moisture contents of the sample streams were determined by manual procedures, as discussed for each test site.

1. Cane Run No. 4, Louisville Gas and Electric Company

A schematic diagram of the monitoring system used at this facility is given in Figure II-1. The sulfur dioxide instrument is a single DuPont 460 four-point, dual range analyzer. The two scrubber module inlet concentrations are measured on a 0-4000 ppm range and the two module outlets after reheating are measured on a 0-500 ppm range. In the event that the module outlet concentrations exceed 500 ppm, the measurement range can be manually switched so that all points are measured on the 0-4000 ppm range. The instrument operates on approximately a 14-minute cycle. During this cycle, each of the four measurement points is sampled. An automatic instrument zero and sample probe backflush occurs

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[2]Mention of a specific company or product name does not constitute endorsement by the Environmental Protection Agency.

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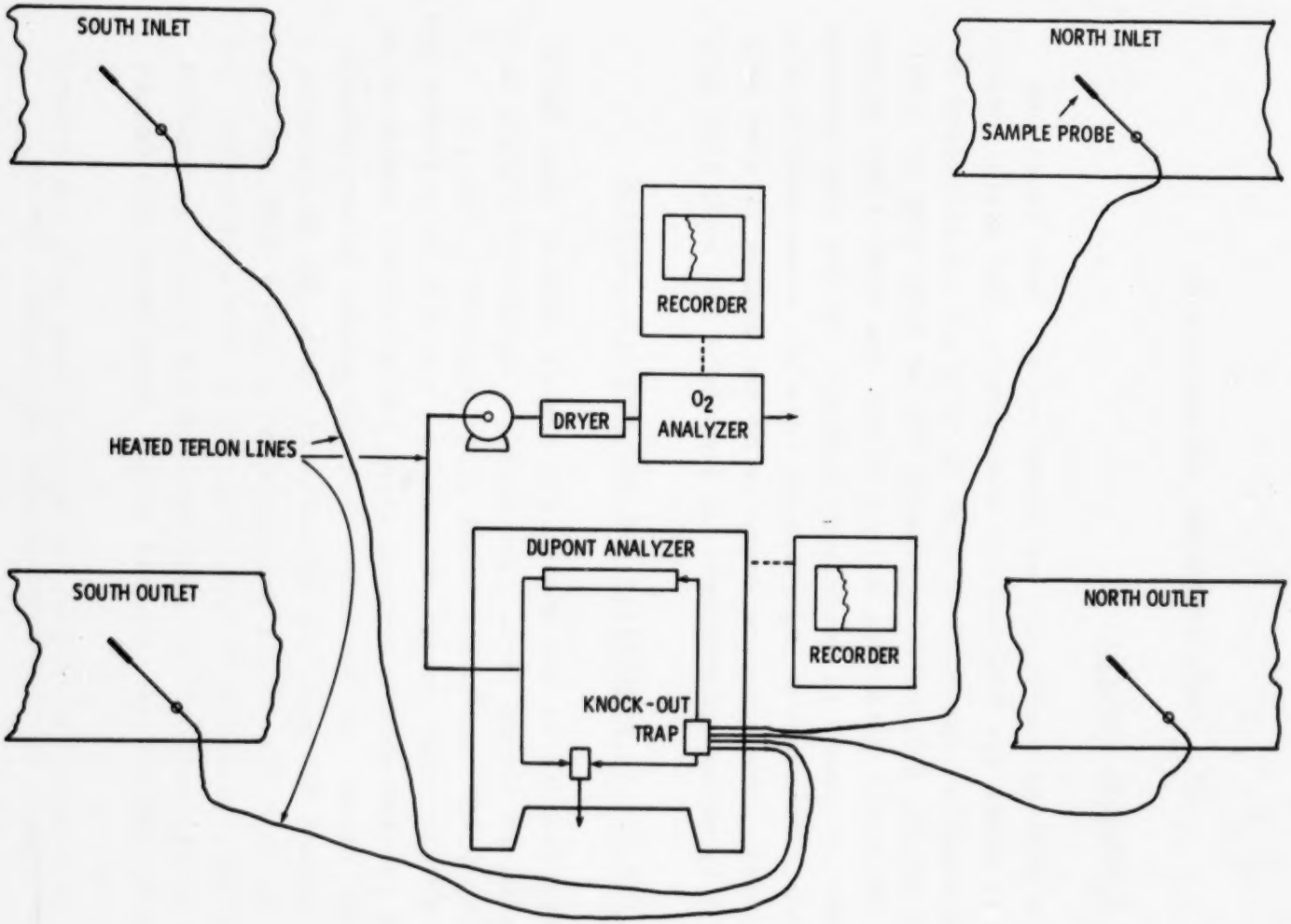

Figure II-1: Instrument System Schematic, Cane Run No. 4
Louisville Gas and Electric Company

immediately prior to each measurement in the cycle. The concentration measurement result is printed on a multipoint chart recorder in the scrubber control room. This concentration record represents the instantaneous value at the time the recorder printer is activated. Therefore, a single instantaneous result is available for each of the four locations in each 14-minute period. A secondary single-pen continuous trace recorder was used as a backup for the control room primary recorder.

The oxygen measurement equipment consisted of a Scott Model 150 paramagnetic analyzer[3]. The sample for oxygen measurement was withdrawn from the Dupont instrument downstream of the sulfur dioxide measurement cell. Therefore, the oxygen measurements were performed on the same sample stream used for sulfur dioxide measurement. Initially, the oxygen analyzer was connected directly to the Dupont analyzer without any further sample conditioning prior to oxygen measurement. The system was later modified to incorporate a condenser for moisture removal prior to oxygen measurement. Oxygen concentrations were determined on a 0-25 percent by volume range. The measurements were recorded on a single-pen continuous trace recorder. For each 14-minute instrument cycle, approximately 2-1/2 minutes of continuous trace record was available for each of the four sample points.

The moisture content of the sample stream was determined by manual techniques. Moisture tests were performed on the scrubber inlet and outlet streams, and on the analyzer sample stream immediately following the knockout trap in the DuPont analyzer. The temperature of the sample stream(s) was also measured. It was found that the sample streams are cooled to approximately 10°C above ambient after the trap. Because of this cooling, the samples were not at stack conditions and were assumed to be

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[3]Mention of a specific company or product name does not constitute endorsement by the Environmental Protection Agency.

saturated at the temperatures measured at the knockout traps. Early in the test program, before the incorporation of a dryer, the moisture content of the oxygen sample stream was the same as that for the sulfur dioxide sample stream. After incorporation of the dryer, the oxygen measurement sample was dry.

A performance specification test was performed on the sulfur dioxide and oxygen instrument system by Scott Environmental Technology, Inc.[4]

The major problem areas encountered during the monitoring program at this facility were interfacing for and measurement of oxygen. It was necessary to modify the sample extraction apparatus and the analyzer itself several times before a satisfactory combination was obtained. The oxygen analyzer was out of service the majority of the period between August to November. While the equipment configuration operated satisfactorily, daily inspection and maintenance were necessary to insure operation.

The only other major problem encountered at this facility was the consistently high oxygen concentrations measured at the scrubber module outlets. It was originally concluded that there was leakage past the blowback air valves installed on the sample probes at these locations. However, later experiments, after replacement of the air valves failed to correct the problem, showed that the placement of the probes was the difficulty. A damper is located upstream of the probe and turning vanes in the duct are located immediately after the probe. These physical configurations tend to stratify the flow into the lower half of the duct, especially at low boiler load conditions. The sample probes extended only four feet into the duct from the top, causing the

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[4]EMB Project No. 77-SPP-20, "First Interim Report - Continuous SO_2 Monitoring at Cane Run No. 4, Louisville Gas and Electric Co.". Scott Environmental Technology, December, 1977.

sample to be extracted from an eddy or low flow zone. This problem was corrected by extending the probes to about ten feet into the duct, so that samples were always extracted from the main flow zone in the duct.

Clogging of the sample probes was not a major problem at this facility. Particulates are removed by electrostatic precipitators prior to the inlet sampling locations and the stack gas reheaters prevent wet gas conditions at the outlet sampling locations. The brief outages caused by sample line plugging could have been avoided by using a modified automatic cleaning procedure.

2. Bruce Mansfield Unit 1, Pennsylvania Power Company

A schematic diagram of the monitoring system used at this facility is presented in Figure II-2. The sulfur dioxide instrument used at the inlet manifold is a DuPont Model 460 two-point analyzer. The concentration measurement range is 0-5000 ppmv. The instrument operates on a 10-minute cycle, where each of the two measurement points is sampled for 5 minutes. Immediately prior to each measurement, an automatic instrument zero and probe backflush occurs. The concentration measurement result is recorded on a continuous trace chart recorder in the scrubber control room. For each 10-minute cycle approximately 4-1/2 minutes of continuous chart record are available for each inlet location.

The FGD system outlet is equipped with two DuPont 460 four-point, dual range analyzers. Each of these analyzers measures three module outlets and the common reheater outlet. Concentration measurements are normally performed on a 0-500 ppm range, but the range can be manually switched to 0-1000 ppm should 500 ppmv be exceeded. Each instrument normally operates on a 12-minute cycle, where each point is monitored for 3 minutes, with an automatic zero and probe backflush occurring prior to each measurement.

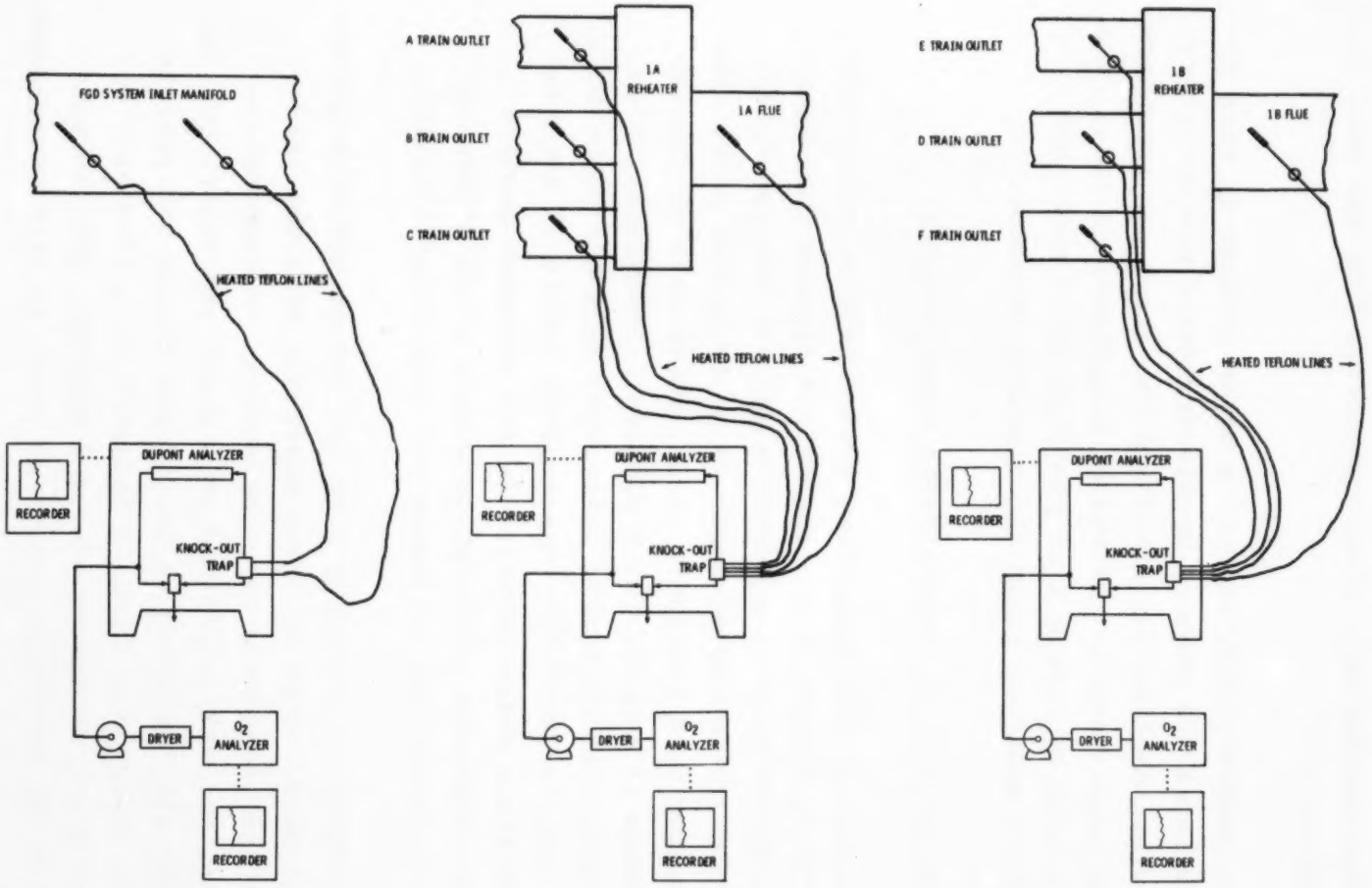

Figure II-2: Instrument System Schematic, Bruce Mansfield No. 1
Pennsylvania Power Company

However, for this program, the three module outlets were not monitored.

The concentration measurement result is printed on a multipoint chart recorder in the scrubber control room. This concentration record represents the instantaneous value at the time the recorder printer is activated. Therefore, a single instantaneous value was available for each 3-minute period. A secondary single-pen continuous trace recorder was used as a backup for the primary control room recorder.

The oxygen measurement equipment at each location consisted of a Taylor OA137[5] paramagnetic analyzer, with a chiller condenser system for sample gas drying. The sample for oxygen measurement was withdrawn from the DuPont instrument downstream of the measurement cell. The oxygen measurements were conducted on the same sample that the DuPont instrument used for sulfur dioxide measurement. Oxygen concentrations were determined on a 0-25 percent by volume range. The measurements were recorded on a single-pen continuous trace recorder at each inlet and outlet instrument. At the inlet location, oxygen results were available for 4-1/2 minutes at each test point for each 10-minute cycle. At the outlet locations, oxygen data were available for 2-1/2 minutes of each 3-minute cycle. A performance specification test was performed on the sulfur dioxide and oxygen instrument systems by York Research Corporation[6].

The moisture contents of the sample streams were determined by manual procedures. Tests were performed at the inlet and outlet locations, and immediately after the knockout trap in the DuPont

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[5]Mention of a specific company or product name does not constitute endorsement by the Environmental Protection Agency.

[6]EMB Project No. 77-SPP-19, "First Interim Report - Continuous SO_2 Monitoring Program at Bruce Mansfield No. 1, Pennsylvania Power Company", York Research Corporation, January, 1978.

analyzer. It was found that the moisture content of the sample stream after the knockout trap was significantly less than flue gas moisture content, therefore, the measured results at the instrument were used for calculation purposes. Since dryers were incorporated in the oxygen sample conditioning systems, all oxygen measurements are on a dry basis.

The major problems encountered at this facility were the measurement of oxygen and plugging of sample probe filters. The oxygen interface system (pump, chiller, condenser, valving) required a very high maintenance effort to correct plugging and leaks. The chiller system for the gas condenser had numerous breakdowns. The oxygen analyzers also failed due to electronic malfunction. After many modifications to the interface systems, the oxygen analyzer at the inlet location was operated with a much reduced maintenance requirement. The paramagnetic analyzer system at the ABC reheater outlet was never brought to an acceptable operating reliability level. This analyzer was replaced by a Thermox[7] Model WDG Zirconium oxide cell instrument. After this modification, there were no further difficulties with oxygen measurement at that location.

A second problem has been severe plugging problems at the outlet sampling location. During the test program there were problems with the absorber mist eliminator and the stack gas reheaters were not operated, resulting in wet gas conditions. The wet carry-over from the scrubber modules quickly caked on the sample probe filters and could not be cleaned by an air backflush. At times, the operating period between required filter cleaning was only two to three hours. A probe backflush system incorporating a combination of hot water and air was fabricated and installed.

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[7]Mention of a specific company or product name does not constitute endorsement by the Environmental Protection Agency.

This system operated for two weeks with success until water supply lines began freezing due to cold weather.

The oxygen measurement and probe plugging problems were compounded by the physical layout of the monitoring systems at this facility. The control stations and recorders for the sulfur dioxide instruments are located in the control room approximately one hundred yards from the analyzer cabinets. As a further complication, the sampling probes are located about one-hundred yards away from and 150 feet above the analyzer cabinets. Because of these physical separations, two men were required to rigorously calibrate and service the systems.

No major problems were encountered with the operation of the sulfur dioxide monitors other than sample interfacing. A non-linear response was identified at the inlet analyzer during the specification tests and was repaired.

3. La Cygne Unit #1, Kansas City Power and Light Company

A schematic diagram of the equipment used at this facility is given in Figure II-3. The inlet sulfur dioxide instrument is a single-point, dual-range DuPont Model 460 analyzer. Concentration measurements are normally made on a 0-5000 ppm range but can be manually switched to a 0-10,000 ppm range when 5000 ppm values are exceeded. The instrument operates on a 10-minute cycle, with a high pressure probe backflush and an automatic zero every cycle. The measurement result is recorded on a continuous trace chart recorder. A Beckman[8] Model F3 paramagnetic oxygen analyzer was originally installed on the sulfur dioxide sample stream exhaust. However, this arrangement did not function reliably due to interface problems. The system was modified to provide a separate

[8]Mention of a specific company or product name does not constitute endorsement by the Environmental Protection Agency.

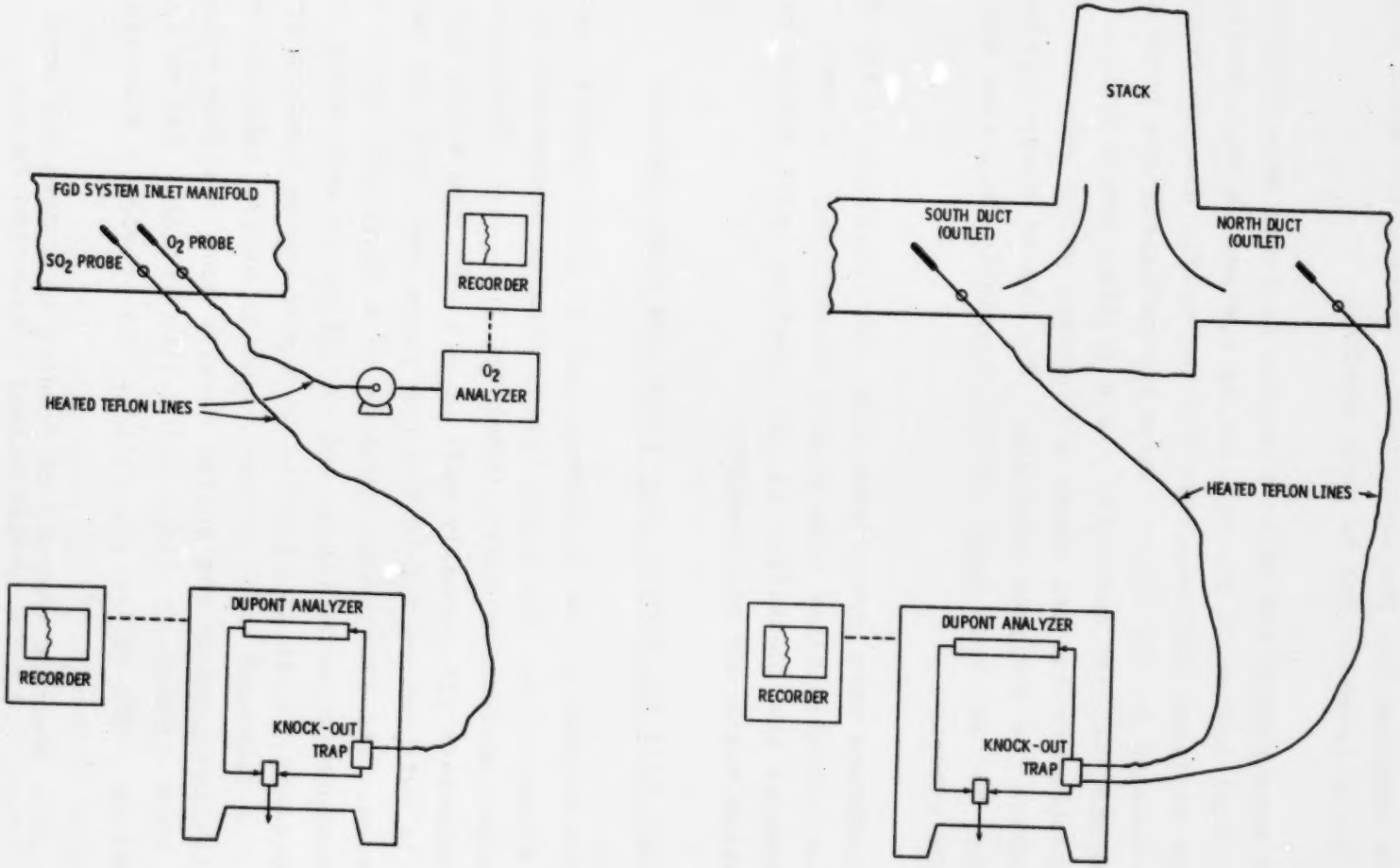

Figure II-3: Instrument System Schematic, La Cygne No. 1
Kansas City Power and Light Company

probe and sample line system for the oxygen analyzer. This arrangement operated satisfactorily.

The outlet sulfur dioxide monitor was a DuPont Model 460 two-point, dual-range analyzer. The concentration measurements were normally conducted on a 0-1500 ppm range, with manual switching capability to a 0-3000 ppm range when the low range was exceeded. The analyzer operated on a 10-minute cycle, with each sample point being analyzed for 5 minutes each cycle. A probe backflush and automatic instrument zero occurs each cycle. The concentration results were recorded on a continuous trace recorder.

A successful oxygen measurement system installation was not completed at the outlet location. After several failures, it was decided that a separate probe and sample line system would be necessary. This system was not installed due to test termination at this facility.

The moisture contents of the sample streams were determined by manual procedures. At the inlet, the flue gas moisture content was measured. At the outlet, the sample stream temperature immediately after the knockout trap was measured and saturated conditions at that temperature were assumed. These moisture contents were always less than those measured at the outlet flue gas ducts.

A performance specification test was conducted on the sulfur dioxide instrument at the outlet location by Environmental Protection Agency personnel.[9] Tests were begun at the inlet analyzer system, but it was determined that repairs to the DuPont instrument were necessary. The performance of the analyzer was significantly improved after replacement of several tubes in the

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[9]"First Interim Report, La Cygne, Kansas Power Plant SO_2 Continuous Monitoring Study", EMB Project No. 77-SPP-22, Environmental Protection Agency, January, 1978.

photometric detector. A retest of the inlet analyzer was not completed due to test program termination.

The only major problem that was encountered other than oxygen measurement was plugging of the sample probe filters at the outlet location. This was due to the wet condition of the stack gas.

4. Eddystone No. 1, Philadelphia Electric Company

A schematic diagram of the monitoring system used at this facility is given in Figure II-4. The sulfur dioxide measurement instrument is a single DuPont Model 460 dual-range, five point analyzer. The FGD system inlet SO_2 concentration is measured on a 0-5000 ppm range, while the system outlet concentration is measured on a 0-500 ppm range. The range is automatically switched depending on the sample being analyzed. The instrument normally operates on a 20-minute cycle with a four-minute analysis at each of the five points. For this program, the instrument was adjusted to measure at only three points.

The concentration measurement result is printed on a multipoint chart recorder in the scrubber control room. This record represents the instantaneous concentration when the recorder printer is activated. Therefore, a single instantaneous result is available for each location in each 12-minute period.

Continuous oxygen measurement was not conducted at this facility. Due to the intermittent operating nature of the FGD system and the problems previously encountered with oxygen measurements, manual procedures were used. The moisture content of the sample streams were determined by manual measurements at each sample site.

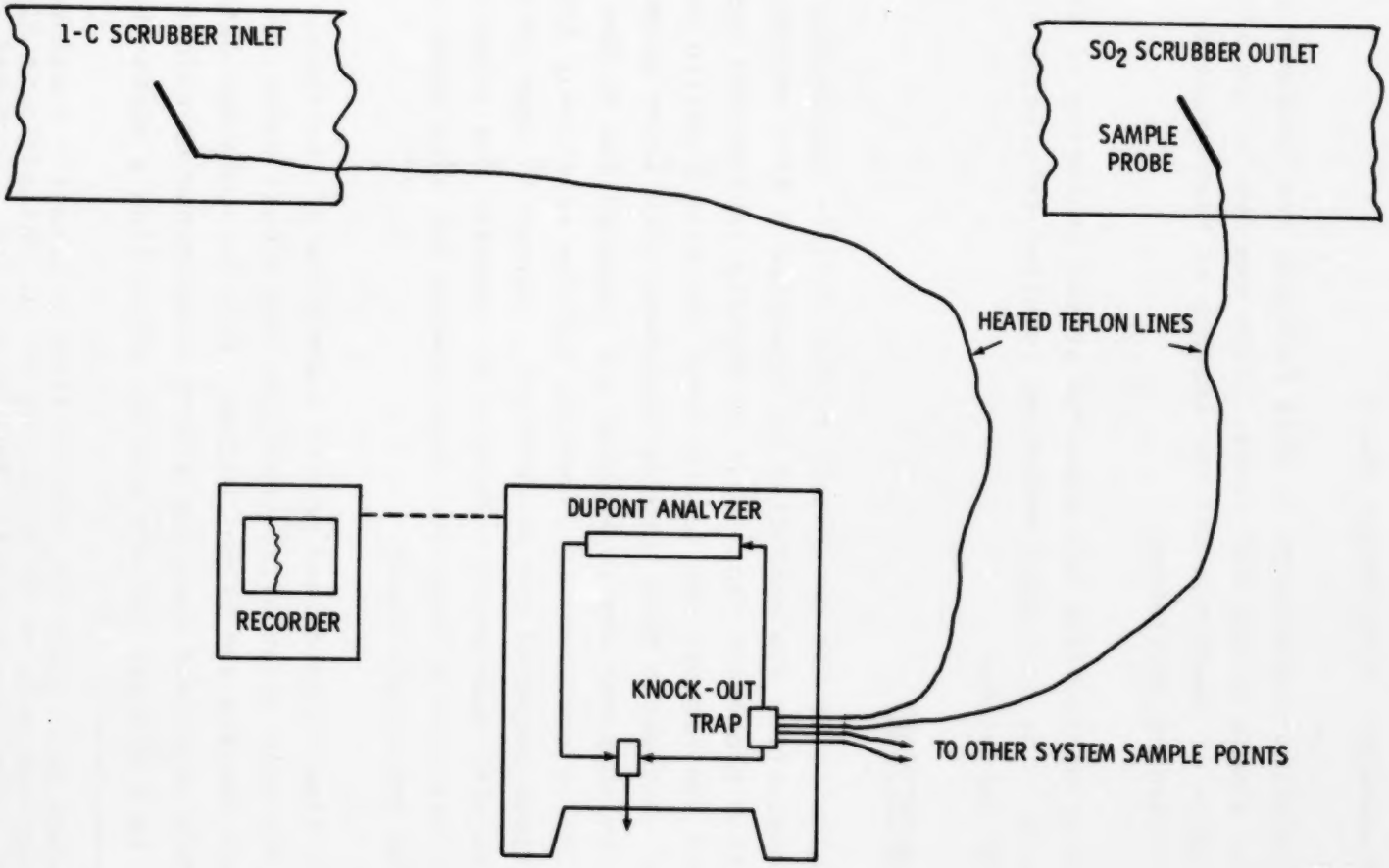

Figure II-4: Instrument System Schematic, Eddystone No. 1
Philadelphia Electric Company

An instrument performance specification test was performed by Scott Environmental Technology, Inc.[10]

The major problem encountered at this facility was frequent clogging of the sample probes and lines. This was due to the intermittent nature of operation and the absence of high-pressure backflush cleaning provisions.

An instrument malfunction was repaired at the beginning of the test program. The auto zero mechanism required rebuilding to obtain proper operation.

B. DATA REDUCTION

At the beginning of the continuous sulfur dioxide monitoring program, an evaluation was conducted to determine a data recording and reduction procedure that could be rapidly implemented and would yield the highest confidence level for data handling reliability. Automatic data logging equipment with later automatic reduction by computer was considered and rejected due to the unavailability of equipment in inventory and the relatively long delivery times required for procurement. Automatic tape recording of data with subsequent reduction by computer was rejected due to the relatively long time requirements for tape translation to computer compatible input.

Due to the time restrictions on the initiation of continuous monitoring, the only alternative remaining was manual reduction of strip chart records and using punched cards for computer data input. This procedure requires a very large manpower effort and would not be practical for any program other than a short-term

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[10]EMB Project No. 77-SPP-20, "First Interim Report - Continuous SO_2 Monitoring Program at Eddystone No. 1, Philadelphia Electric Company", Scott Environmental Technology, Inc., December, 1977.

project. For routine monitoring, an automatic data logging and calculation system is the only feasible approach for the amount of data required to monitor flue gas desulfurization system performance.

Monsanto Research Corporation was responsible for data reduction and summarization in this project. The strip chart records were collected from the recorders along with copies of the appropriate boiler and scrubber control room logs at weekly intervals by the contractors operating the monitoring systems at the test sites. These were: Bruce Mansfield No. 1 - York Research Corporation; La Cygne No. 1 - Midwest Research Institute; Cane Run No. 4; and Eddystone No. 1 - Scott Environmental Technology, Inc.

The site contractors also provided narrative logs regarding instrument system performance and calibrations during the weekly operating period.

A partial listing of the types of data that were received from each test site is given below:

Cane Run No. 4

SO_2 strip chart (2 outlets - 2 inlets on same chart)
O_2 strip chart (2 outlets - 2 inlets on same chart)
Scrubber logs
Boiler logs
Calibration information

Bruce Mansfield No. 1

SO_2 inlet chart
O_2 inlet chart
SO_2 outlet chart
O_2 outlet chart

Bruce Mansfield No. 1 (Continued)

Scrubber logs
Boiler logs
Additional comments on a daily basis

Eddystone No. 1

SO_2 strip charts (inlet-outlet on same chart)
Boiler logs
Scrubber logs
Manual test results and daily comments

La Cygne No. 1

SO_2 inlet chart
O_2 inlet chart
SO_2 outlet chart
Daily comments

Samples of the chart records from Cane Run No. 4 are presented in Figure II-5.

The chart records were first logged in as received and then were reviewed for possible data gaps. The charts were then reduced to tabular format as shown in Figure II-6. Where only a single instantaneous point was available in a 15-minute period, that result was used. When more than one point, or where a longer continuous record was available in a 15-minute period, the average value was entered for a 15-minute value. The unit load vales were obtained from the boiler logs.

After data transcription the boiler logs, scrubber logs, and daily narratives were reviewed so that appropriate comments could be included prior to data listing.

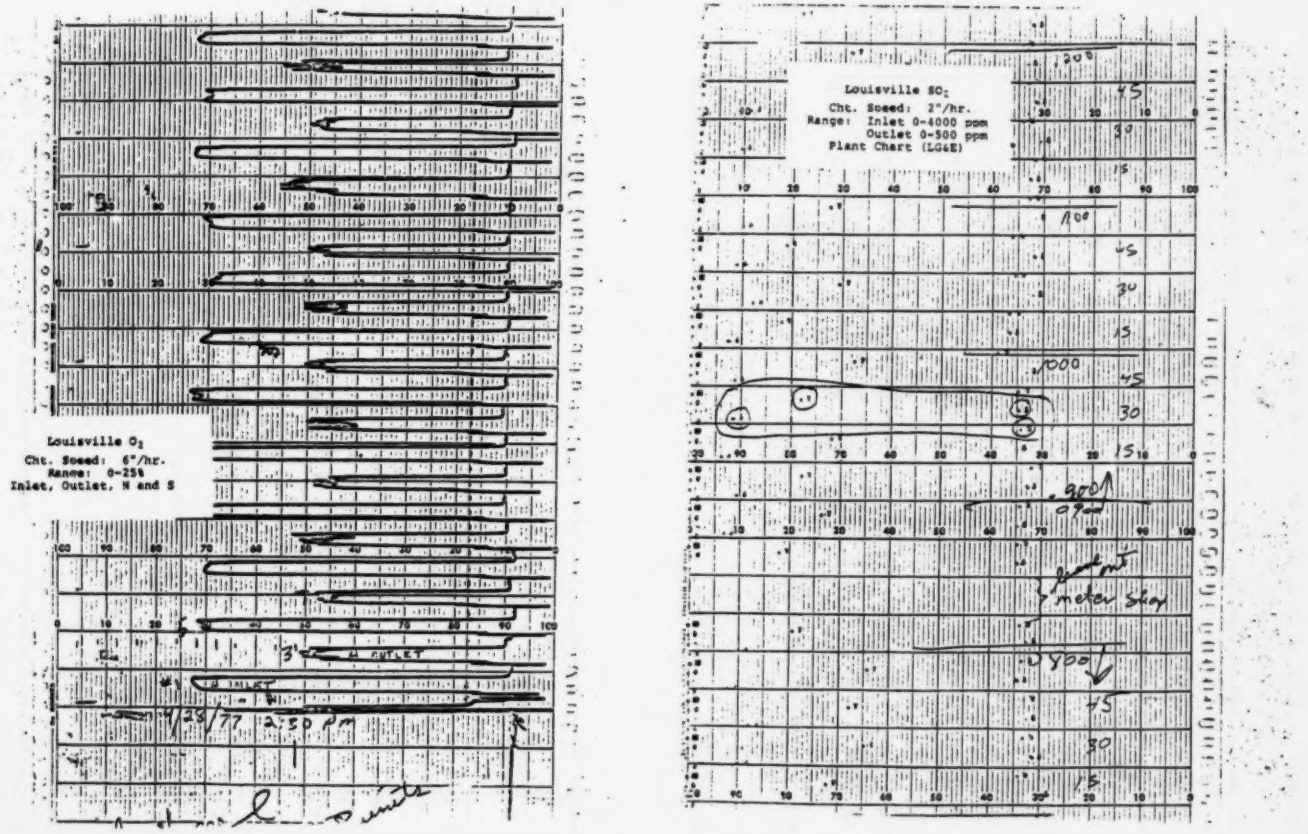

Figure II-5: Sample Strip Chart Data

LOUISVILLE SO_2 DATA
(transcribed from strip chart)

Date	Time	Boiler Load	North Scrubber In	North Scrubber Out	South Scrubber In	South Scrubber Out
		BLR	1	3	5	7
10-11	1000	95	70	21	67	26
	15		73	25	70	38
	30		74	25	70	23
	45		73	25	71	40
	1100	100	71	23	73	23
	15		72	24	71	27
	30		73	21	72	34
	45		73	25	74	31
	1200	102	78	23	76	43
	15		76	19	76	28
	30		76	32	75	42
	45		78	19	75	23
	1300	105	76	19	74	44
	15		78	23	76	27
	30		77	23	77	42
	45		72	16	73	26
	1400	102	75	20	75	40
	15		78	19	77	27
	30		77	23	75	32
	45		78	20	76	32
	1500	100	78	26	76	46
	15		79	27	78	31
	30		76	27	79	45
	45		75	18	75	28

LOUISVILLE OXYGEN DATA
(transcribed from strip chart)

			O_2 Data			
Date	Time	Boiler Load	North Scrubber In	North Scrubber Out	South Scrubber In	South Scrubber Out
		BLR	1	3	5	7
9-22	0430		6	12	6	13
	45		6	11	6	13
	0500		6	11.5	6	12
	15		6	10.5	5.5	12.5
	30		6	10.5	6	13
	45		6	10	5.5	12.5
	0600		6	12.5	6	12.5
	15		6	11	6	13
	30		6	11	6	13
	45		6	11	5.5	12.5
	0700		6	12	6	13
	15		6	11	6	13
	30		6	12	6	13
	45		6	13	6	11
	0800		6	12.5	6	13.5
	15		6	12	6	13
	30		6	12.5	6	13
	45		6.5	12.5	6	13
	0900		6	12	5	12.5
	15		6	12	6	12
	30		6	11.5	5.5	12
	45		6	11.5	5.5	12
	1000		6	10	5	12
	15		8	11	6	12.5
	30		8.5	11	6	12
	45		8	11.5	5.5	11.5
	1100		8.5	11	6	12

Figure II-6: Sample Data Transcription Form

The transcribed data were then audited by spot-checking a 15-minute data point for each day of transcribed data. After audited, the data were keypunched and processed by computer to obtain a data listing and calculated results for each 15-minute data point. The computer listings were reviewed for keypunch or other transcription errors. The listings were then sent to EPA for editing. This edit procedure incorporated the review of boiler, scrubber, and instrument operating logs so that periods of scrubber outage, bypass, startup or shutdown could be identified and coded so that these data would not be included in the calculation of averages and summaries. A sample of a 15-minute data listing at Cane Run No. 4 is presented in Figure II-7. For this system there are two separate inlets and outlets. The data listing format is the same at the other facilities except that no results are entered in the appropriate columns where less than two inlets or two outlets are present.

After data editing was completed, average summaries were prepared. Averages based on the 15-minute data were prepared for consecutive 1-hour, 3-hour, 8-hour, and 24-hour intervals. In order to calculate an average result for a single interval, it was specified that at least 75 percent of the 15-minute data points be available for that interval. For example, an 8-hour average could only be calculated when 24 of the possible 32 15-minute data points were available. When less than 75 percent of the data were available for an interval, an average was not calculated and blanks were entered in the summary printouts.

After each 30 days of average interval data, a statistical summary was prepared. The parameters calculated were the mean (based on the interval averages), and the statistical measures of variation. Samples of 24-hour interval averages and the statistical summary of the averages are given in Figure II-8.

LOUISVILLE				INLET (NORTH)				OUTLET (NORTH)					INLET (SOUTH)				OUTLET (SOUTH)				
DATE	TIME	BLR LOAD MW	CD	SO2 CONC PPM WET	O2 CONC PCT	H2O PCT	LB/ MMBTU	SO2 CONC PPM WET	O2 CONC PCT	H2O PCT	LB/ MMBTU	EFF	SO2 CONC PPM WET	O2 CONC PCT	H2O PCT	LB/ MMBTU	SO2 CONC PPM WET	O2 CONC PCT	H2O PCT	LB/ MMBTU	EFF
	30	107	0	2572	4.9	6.1	5.944	244	7.1	6.9	0.674	88.7	2572	4.9	6.1	5.944	284	7.1	6.9	0.782	86.8
	45	107	0	2572	4.9	6.1	5.944	186	7.1	6.9	0.513	91.4	2532	4.9	6.1	5.850	293	7.1	6.9	0.809	86.2
081077	0600	134	0	2654	4.9	6.1	6.133	269	7.1	6.9	0.742	87.9	2777	4.9	6.1	6.416	333	7.1	6.9	0.917	85.7
	15	134	0	2654	4.9	6.1	6.133	259	7.1	6.9	0.715	88.3	2736	4.9	6.1	6.322	440	7.1	6.9	1.214	80.8
	30	134	0	2654	4.9	6.1	6.133	259	7.1	6.9	0.715	88.3	2654	4.9	6.1	6.133	387	7.1	6.9	1.066	82.6
	45	134	0	2695	4.9	6.1	6.227	244	7.1	6.9	0.674	89.2	2736	4.9	6.1	6.322	440	7.1	6.9	1.214	80.8
081077	0700	145	0	2940	4.9	6.1	6.794	293	7.1	6.9	0.809	88.1	2654	4.9	6.1	6.133	367	7.1	6.9	1.012	83.5
	15	145	0	2613	4.9	6.1	6.039	244	7.1	6.9	0.674	88.8	2777	4.9	6.1	6.416	342	7.1	6.9	0.944	85.3
	30	145	0	2940	4.9	6.1	6.794	308	7.1	6.9	0.850	87.5	2736	4.9	6.1	6.322	318	7.1	6.9	0.877	86.1
	45	145	0	2041	4.9	6.1	4.718	303	7.1	6.9	0.836	82.3	2940	4.9	6.1	6.794	313	7.1	6.9	0.863	87.3
081077	0800	160	0	2082	4.9	6.1	4.812	298	7.1	6.9	0.823	82.9	3267	4.9	6.1	7.548	298	7.1	6.9	0.823	89.1
	15	160	0	2409	4.9	6.1	5.567	293	7.1	6.9	0.809	85.5	3553	4.9	6.1	8.209	293	7.1	6.9	0.809	90.1
	30	160	0	2041	4.9	6.1	4.718	298	7.1	6.9	0.823	82.6	2532	4.9	6.1	5.850	293	7.1	6.9	0.809	86.2
	45	160	0	3022	4.9	6.1	6.982	298	7.1	6.9	0.823	88.2	3757	4.9	6.1	8.681	298	7.1	6.9	0.823	90.5
081077	0900	160	0	2491	4.9	6.1	5.756	293	7.1	6.9	0.809	85.9	3675	4.9	6.1	8.492	293	7.1	6.9	0.809	90.5
	15	160	0	3062	4.9	6.1	7.077	298	7.1	6.9	0.823	88.4	3226	4.9	6.1	7.454	293	7.1	6.9	0.809	89.1
	30	160	0	2572	4.9	6.1	5.944	298	7.1	6.9	0.823	86.2	3634	4.9	6.1	8.398	293	7.1	6.9	0.809	90.4
	45	160	0	3226	4.9	6.1	7.454	298	7.1	6.9	0.823	89.0	3471	4.9	6.1	8.020	293	7.1	6.9	0.809	89.9
081077	1000	160	0	2491	4.9	6.1	5.756	328	7.1	6.9	0.904	84.3	2491	4.9	6.1	5.756	460	7.1	6.9	1.268	78.0
	15	160	0	2450	4.9	6.1	5.661	391	7.1	6.9	1.079	80.9	2450	4.9	6.1	5.661	347	7.1	6.9	0.958	83.1
	30	160	0	2450	4.9	6.1	5.661	303	7.1	6.9	0.836	85.2	2450	4.9	6.1	5.661	416	7.1	6.9	1.147	79.7
	45	160	0	2450	4.9	6.1	5.661	387	7.1	6.9	1.066	81.2	2450	4.9	6.1	5.661	347	7.1	6.9	0.958	83.1
081077	1100	160	0	2450	4.9	6.1	5.661	333	7.1	6.9	0.917	83.8	2450	4.9	6.1	5.661	391	7.1	6.9	1.079	80.9
	15	160	0	2450	4.9	6.1	5.661	401	7.1	6.9	1.106	80.5	2450	4.9	6.1	5.661	352	7.1	6.9	0.971	82.8
	30	160	0	2409	4.9	6.1	5.567	328	7.1	6.9	0.904	83.8	2450	4.9	6.1	5.661	391	7.1	6.9	1.079	80.9
	45	160	0	2409	4.9	6.1	5.567	347	7.1	6.9	0.958	82.8	2450	4.9	6.1	5.661	357	7.1	6.9	0.985	82.6
081077	1200	160	0	2409	4.9	6.1	5.567	333	7.1	6.9	0.917	83.5	2450	4.9	6.1	5.661	401	7.1	6.9	1.106	80.5
	15	160	0	2409	4.9	6.1	5.567	416	7.1	6.9	1.147	79.4	2409	4.9	6.1	5.567	391	7.1	6.9	1.079	80.6
	30	160	0	2409	4.9	6.1	5.567	328	7.1	6.9	0.904	83.8	2450	4.9	6.1	5.661	406	7.1	6.9	1.120	80.2
	45	160	0	2409	4.9	6.1	5.567	357	7.1	6.9	0.985	82.3	2409	4.9	6.1	5.567	391	7.1	6.9	1.079	80.6
081077	1300	160	0	2409	4.9	6.1	5.567	249	7.1	6.9	0.688	87.6	2409	4.9	6.1	5.567	436	7.1	6.9	1.201	78.4
	15	160	0	2409	4.9	6.1	5.567	352	7.1	6.9	0.971	82.6	2409	4.9	6.1	5.567	352	7.1	6.9	0.971	82.6
	30	160	0	2409	4.9	6.1	5.567	328	7.1	6.9	0.904	83.8	2409	4.9	6.1	5.567	328	7.1	6.9	0.904	83.8
	45	160	0	2409	4.9	6.1	5.567	382	7.1	6.9	1.052	81.1	2409	4.9	6.1	5.567	382	7.1	6.9	1.052	81.1
081077	1400	160	0	2368	4.9	6.1	5.473	293	7.1	6.9	0.809	85.2	2409	4.9	6.1	5.567	347	7.1	6.9	0.958	82.8
	15	160	0	2409	4.9	6.1	5.567	352	7.1	6.9	0.971	82.6	2409	4.9	6.1	5.567	367	7.1	6.9	1.012	81.8
	30	160	0	2409	4.9	6.1	5.567	303	7.1	6.9	0.836	85.0	2450	4.9	6.1	5.661	342	7.1	6.9	0.944	83.3
	45	160	0	2450	4.9	6.1	5.661	387	7.1	6.9	1.066	81.2	2409	4.9	6.1	5.567	387	7.1	6.9	1.066	80.9
081077	1500	160	0	2409	4.9	6.1	5.567	289	7.1	6.9	0.796	85.7	2450	4.9	6.1	5.661	362	7.1	6.9	0.998	82.4
	15	160	0	2409	4.9	6.1	5.567	333	7.1	6.9	0.917	83.5	2409	4.9	6.1	5.567	362	7.1	6.9	0.998	82.1
	30	160	0	2368	4.9	6.1	5.473	342	7.1	6.9	0.944	82.7	2368	4.9	6.1	5.473	333	7.1	6.9	0.917	83.2
	45	160	0	2368	4.9	6.1	5.473	323	7.1	6.9	0.890	83.7	2368	4.9	6.1	5.473	338	7.1	6.9	0.931	83.0
081077	1600	150	0	2532	4.9	6.1	5.850	342	7.1	6.9	0.944	83.9	2368	4.9	6.1	5.473	308	7.1	6.9	0.850	84.5
	15	150	0	2858	4.9	6.1	6.605	279	7.1	6.9	0.769	88.4	2532	4.9	6.1	5.850	279	7.1	6.9	0.769	86.9
	30	150	0	2450	4.9	6.1	5.661	284	7.1	6.9	0.782	86.2	2858	4.9	6.1	6.605	293	7.1	6.9	0.809	87.7
	45	150	0	3062	4.9	6.1	7.077	293	7.1	6.9	0.809	88.6	2940	4.9	6.1	6.794	284	7.1	6.9	0.782	88.5
081077	1700	160	0	2450	4.9	6.1	5.661	284	7.1	6.9	0.782	86.2	2736	4.9	6.1	6.322	284	7.1	6.9	0.782	87.6
	15	160	0	2817	4.9	6.1	6.510	284	7.1	6.9	0.782	88.0	2817	4.9	6.1	6.510	284	7.1	6.9	0.782	88.0

Figure II-7: Sample Data Listing

24 HOUR AVGS LOUISVILLE			IN(NORTH)		OUT(NORTH)			IN(SOUTH)		OUT(SOUTH)			INLET TOTAL	OUTLET TOTAL	
DATE	TIME	NPS	SO2 PPM DRY	LB/ MMBTU	SO2 PPM DRY	LB/ MMBTU	EFF	SO2 PPM DRY	LB/ MMBTU	SO2 PPM DRY	LB/ MMBTU	EFF	LB/ MMBTU	LB/ MMBTU	TOTAL EFFY
072177	1200	48	----	-----	----	-----	---	----	-----	----	-----	---	-----	-----	----
072277	2400	96	2389	5.184	133	0.342	93.4	2830	6.140	95	0.244	96.0	5.662	0.293	94.8
072377	2400	71	----	-----	----	-----	---	----	-----	----	-----	---	-----	-----	----
072477	2400	75	2875	6.238	27	0.070	98.9	2911	6.314	20	0.050	99.2	6.276	0.060	99.0
072577	2400	96	2904	6.300	34	0.088	98.6	2920	6.335	23	0.060	99.1	6.318	0.074	98.8
072677	2400	96	2843	6.167	34	0.088	98.6	2934	6.365	30	0.078	98.8	6.266	0.083	98.7
072777	2400	63	----	-----	----	-----	---	----	-----	----	-----	---	-----	-----	----
080877	0900	59	----	-----	----	-----	---	----	-----	----	-----	---	-----	-----	----
080977	2400	85	2787	6.045	277	0.710	88.2	2812	6.100	352	0.854	85.5	6.073	0.782	87.1
081077	2400	96	2844	6.169	290	0.744	87.8	2876	6.239	332	0.851	86.2	6.204	0.797	87.1
081177	2400	94	2018	4.403	373	0.956	83.9	2969	6.341	394	0.936	83.7	5.372	0.946	82.4
081277	2400	90	2649	5.746	411	1.024	81.8	2677	5.808	383	0.981	82.9	5.777	1.002	82.6
081377	1100	52	----	-----	----	-----	---	----	-----	----	-----	---	-----	-----	----
081477	2400	70	----	-----	----	-----	---	----	-----	----	-----	---	-----	-----	----
081577	1100	51	----	-----	----	-----	---	----	-----	----	-----	---	-----	-----	----
081677	2400	89	3175	6.887	510	1.307	81.2	3196	6.934	506	1.267	81.4	6.911	1.287	81.4
081777	2400	96	2903	6.298	227	0.581	91.0	2878	6.243	244	0.626	90.2	6.271	0.603	90.4
081877	2400	48	----	-----	----	-----	---	----	-----	----	-----	---	-----	-----	----
082277	0400	79	2492	5.405	430	0.960	79.6	2224	4.825	427	1.058	75.2	5.115	1.009	80.3
082377	2400	96	2667	5.786	391	1.002	82.7	2635	5.715	395	0.997	82.4	5.750	0.999	82.6
082477	2400	91	2906	6.304	353	0.906	85.7	2885	6.260	372	0.954	84.8	6.282	0.930	85.2
082577	2400	86	2741	5.951	287	0.737	87.7	2734	5.935	327	0.839	86.0	5.943	0.788	86.7
082677	2400	96	2709	5.882	368	0.945	83.9	2758	5.987	411	1.056	82.4	5.935	1.001	83.1
082777	2400	90	2503	5.434	358	0.920	83.5	2599	5.642	389	0.967	83.0	5.538	0.944	83.0
082877	2400	96	2695	5.851	371	0.953	83.8	2726	5.918	422	1.071	80.9	5.885	1.012	82.8
082977	2400	96	2633	5.717	357	0.918	84.0	2665	5.787	419	1.076	81.5	5.752	0.997	82.7
083077	2400	96	2858	6.206	424	1.089	82.6	2861	6.210	483	1.240	80.2	6.208	1.165	81.2
083177	2400	96	3023	6.564	516	1.326	79.9	3052	6.625	572	1.469	78.0	6.595	1.397	78.8
090177	2400	96	2508	5.447	362	0.930	83.1	2588	5.619	421	1.081	80.8	5.533	1.006	81.8
090277	2400	94	2351	5.108	290	0.744	85.4	2535	5.504	391	1.003	81.9	5.306	0.874	83.5

24 HOUR AVGS LOUISVILLE	IN(NORTH)		OUT(NORTH)			IN(SOUTH)		OUT(SOUTH)			INLET TOTAL	OUTLET TOTAL	
30 DAY STATS	SO2 PPM DRY	LB/ MMBTU	SO2 PPM DRY	LB/ MMBTU	EFF	SO2 PPM DRY	LB/ MMBTU	SO2 PPM DRY	LB/ MMBTU	EFF	LB/ MMBTU	LB/ MMBTU	TOTAL EFFY
MEAN	2703.	5.868	310.	0.788	86.6	2785.	6.038	337.	0.853	85.5	5.953	0.820	86.1
STD DEVIATION	255.6	0.5508	141.3	0.3572	5.94	203.7	0.4377	156.7	0.3976	6.89	0.438	0.375	6.3
AVG DEVIATION	193.5	0.4179	108.4	0.2718	4.67	155.1	0.3313	116.8	0.2928	5.20	0.352	0.280	4.9
MAXIMUM	3175.	6.887	516.	1.326	98.9	3196.	6.934	572.	1.469	99.2	6.911	1.397	99.0
MINIMUM	2018.	4.403	27.	0.070	79.6	2224.	4.825	20.	0.050	75.2	5.115	0.060	78.8
RANGE	1156.	2.484	489.	1.256	19.3	972.	2.109	552.	1.419	24.0	1.795	1.337	20.2
PCT ST DEV	9.45	9.387	45.55	45.314	6.9	7.32	7.249	46.53	46.622	8.1	7.354	45.740	7.3

Figure II-8: Sample Average Listing and Statistical Summary

A second statistical computation was performed for the sulfur dioxide removal efficiencies of the FGD systems. This procedure calculated a frequency distribution for the percent occurrence of sulfur dioxide removal efficiencies for each averaging interval.

The calculation procedures used to convert the analyzer outputs for sulfur dioxide and oxygen concentrations to mass emission factors are given in 40 CFR 60 Subpart D. This procedure is known as the F-factor approach and is given below:

$$E = \frac{CFK}{1-M} \times \left[\frac{20.9}{20.9 - \frac{O_2}{1-M}} \right]$$

Where E = Emission factor - lb/million Btu

C = SO_2 concentration - ppmv, wet basis

F = Stoichiometric conversion factor, 9820 dscf/million Btu for subbituminous coal

K = Conversion factor, 1.659×10^{-7} lb/dscf per ppmv

O_2 = Oxygen concentration, percent by volume as measured

M = Moisture fraction as measured (for dried samples, M=0)

The sulfur dioxide and oxygen concentration results were obtained by multiplying the strip chart readings as a percent of scale by the appropriate calibration factor.

The emission factor was calculated for each FGD system inlet and outlet test point. The sulfur dioxide removal efficiency for a module or set of modules is calculated by:

$$\text{Efficiency} = \frac{Ein - E\ out}{Ein} \times 100\%$$

When more than inlet and/or outlet test point was monitored, the total system emission factors and sulfur dioxide removal efficiencies were calculated by a weighted average procedure. The equation for this calculation for total system efficiency is given by:

$$EFF\ total = EFF_A(F_A) + EFF_B(F_B)$$

Where,

EFF_{total} = total system efficiency

EFF_A = efficiency of module or module set A

F_A = fraction of gas flow through module or model set A

EFF_B = efficiency of module or module set B

F_B = fraction of gas flow through module or module set B

For all data in this study the scrubber systems have operated such that the flows through two module sets have been essentially equal, or there has only been one module set operating. Thus, a simple average has been used for total system performance.

The major problems that were encountered in the data reduction procedures were related to strip chart records. Cases were encountered where time, periods of chart stops, starts, and advances, and unmarked instrument range changes, were not properly noted, as well as periods when pens failed to ink. These problems were corrected by requiring that the site contractors devote additional attention to assuring that accurate and adequately informative chart records were obtained. During data editing, the

boiler, scrubber, and instrument log sheets were adequate to describe periods of missing or unuseable data.

C. IMPROVEMENTS AND RESEARCH NEEDED

The majority of the problems encountered in this program were due to the necessity of using previously installed instrumentation and adapting other instrumentation into a system that was not designed as a unit and as such, could not perform at optimum levels. For example, most of the sulfur dioxide instruments were ordered and installed five to seven years ago when less was known about the most useful installation locations. Additionally, in some cases the instrument systems were never properly installed and operated.

None of the sulfur dioxide systems were designed to allow straightforward measurement of oxygen. In order to meet the program time objectives, available oxygen measurement equipment had to be adapted and this adaptation was time consuming and required more maintenance effort than is desirable.

It appears that the modification to the probe backflush system which incorporated a combination of water and air will solve the probe plugging problems in those cases where dry air is not an adequate cleaning procedure.

While the present procedure for moisture content of the sample streams is adequate for intensive monitoring efforts where manpower is continuously available to record results, this procedure is not a desirable long-term approach. Research is recommended to define the moisture measurement requirements of various instrument systems, and the best way to achieve these requirements. This result could either be by continuous instrumentation for moisture measurement, or by sample conditioning to a known standard condition.

The improvement that will provide the greatest benefit is an automatic data logging and calculation system. This has been the most time consuming part of this program and manual data analysis is not recommended for routine purposes. Data processing equipment suitable for this purpose is commercially available.

In summary, the monitoring system operating problems that have been encountered in this program have been the result of inadequate initial system design, or the compromises made in the interest of rapid test initiation. Based on the experience developed in this program, a monitoring system that would be convenient to use, yield high operating reliability, and provide data automatically converted to the units of the standard could be designed.

III. DATA ANALYSIS

A. DATA COLLECTION INTERVAL SELECTION

At the beginning of the monitoring program it was necessary to establish a minimum data collection frequency. Since essentially all of the installed sulfur dioxide systems were multiple sampling point analyzers, no truly continuous measurements would be available. Review of the systems indicated that a 15-minute cycle for a 4-point analyzer was the practical minimum. Since all other analyzers would yield at least one result during a 15-minute cycle, this was selected as a standard collection frequency for all sites to maintain calculation consistency. For those systems where either a multiple number of instantaneous values, or a period of continuous values are available in a 15-minute period, the average of these values is used as the data point. This procedure is valid so long as the measured parameters do not vary significantly during a 15-minute period. Samples of the output at an inlet and outlet test point at Cane Run No. 4 where the analyzer was held in a continuous mode are given in Figures III-1 and III-2. The inlet sulfur dioxide concentrations are essentially constant over a 15-minute period. The outlet sulfur dioxide concentrations vary about ± 1 to 2 scale divisions about the mean during a 15-minute period. For readings greater than 50 percent of full scale, the potential variation for an instantaneous reading from the 15-minute mean would be at most ± 4 percent of the concentration result. This estimate is based on steady operation at constant load.

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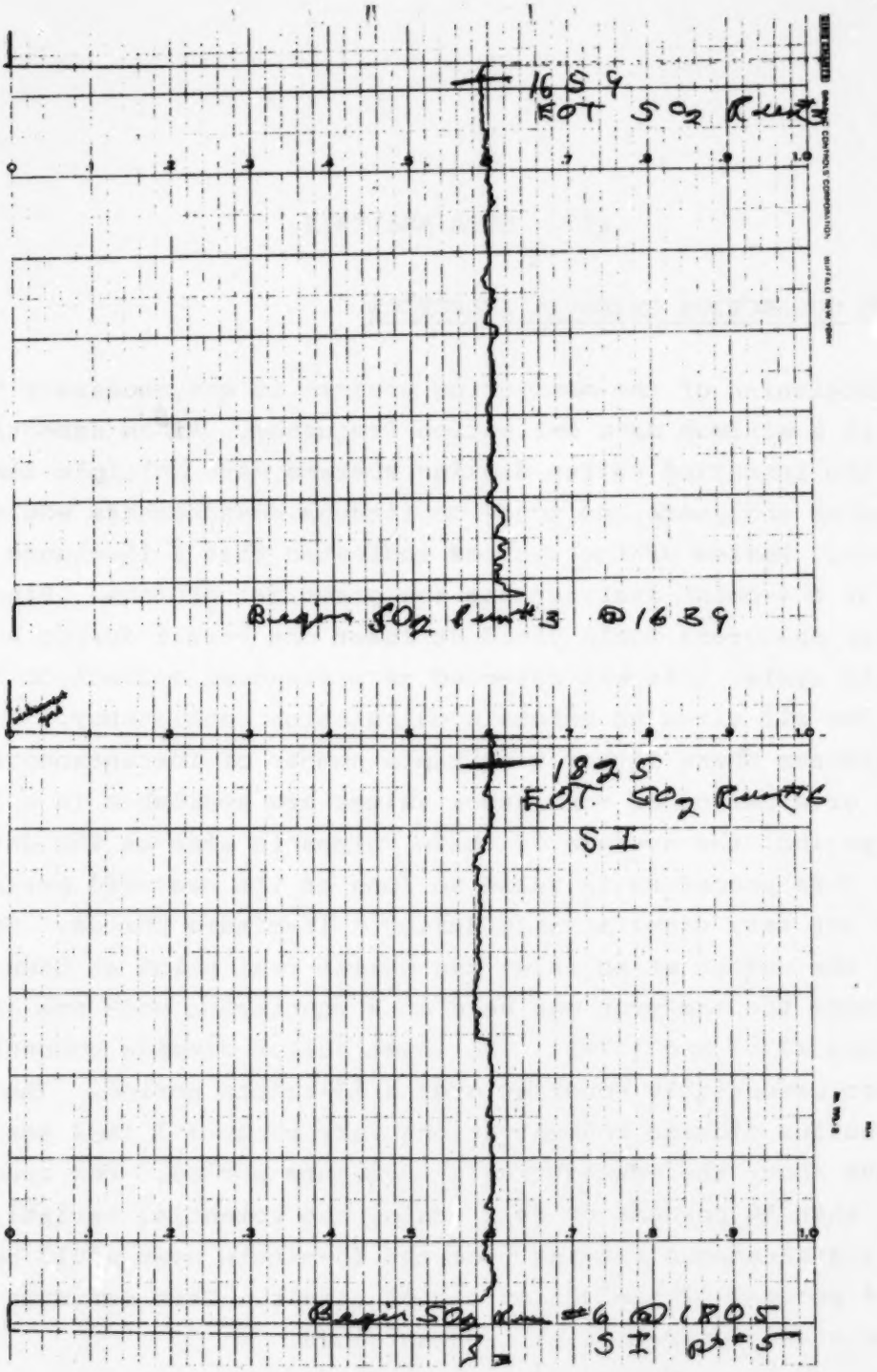

Figure III-1: Inlet SO_2 Variation, Cane Run No. 4

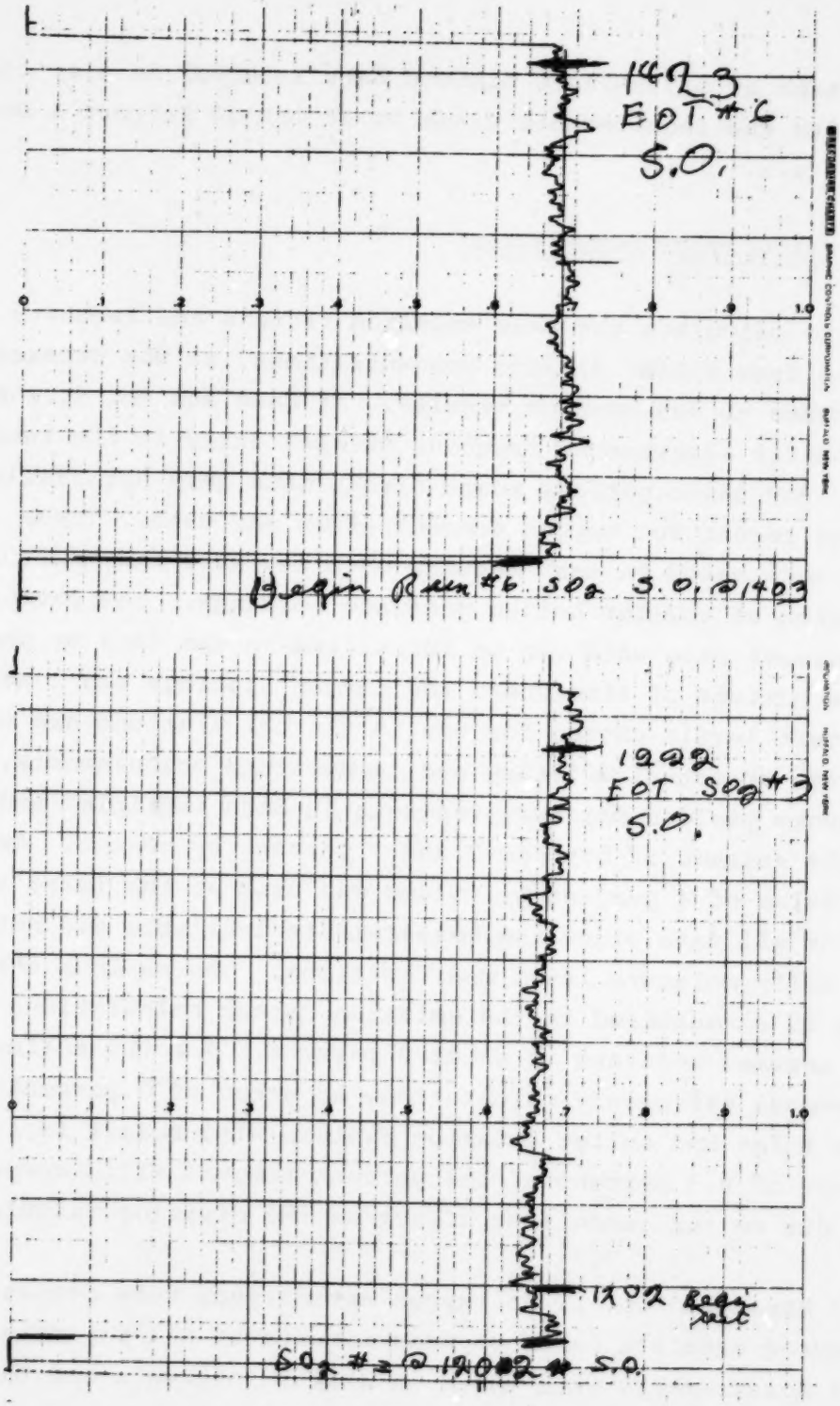

Figure III-2: Outlet SO_2 Variation, Cane Run No. 4

The selection of a 15-minute minimum data interval is also consistent with the requirements given in 40 CFR 60 Subpart A Section 60.13.e.z.

B. DATA CALCULATION ASSUMPTIONS

In order to calculate the mass emission factors and recovery efficiencies from sulfur dioxide concentrations, it was necessary in some cases to use average results. At Cane Run No. 4, the oxygen monitor experienced frequent outages early in the test program. For those periods where oxygen data were not available, an average result for oxygen concentration was used. These averages were based on test results obtained when the monitor was in operation at similar boiler megawatt loadings. The periods where averages were used can be identified in the data by observing those periods of time where the oxygen listings are constant. The moisture levels chosen for use in the calculations are based on a series of actual moisture and temperature measurements. The measurements yielded moisture contents in both the inlet and outlet sample streams of between 2 and 7 percent by volume. An average value of 4 percent by volume was used at the inlet and outlet for all data since the measurements available did not justify daily moisture level modifications. The maximum error that can be encountered in the emission factor calculations due to this assumed moisture is about 3 percent. For the sulfur dioxide removal efficiency calculation, an error of 3 percent in both the inlet and outlet emission factors will result in a maximum error of 0.5 percent of the percent removal efficiency. This is due to the cancelling effect of the division calculation.

At Bruce Mansfield No. 1, no oxygen estimations were necessary. The reported data are based on measurements of all parameters. Moisture measurements were taken at weekly intervals and the results for that week were used in the calculations.

At Eddystone No. 1, oxygen measurements were by manual procedures during the scrubber operating periods. It was found that the variability was small and, therefore, one average result was used for inlet and outlet. Moisture levels were based on manual measurements.

At La Cygne No. 1, oxygen data on a limited basis were available for the inlet location. No data were available for the outlet. For estimation purposes, the outlet oxygen concentration was assumed to be equal to the inlet. This calculation yields only an estimate of the sulfur dioxide efficiency since there is probably some dilution between the inlet and outlet measurement points. Moisture levels were chosen based on average results obtained by manual measurements. Because no complete outlet data were gathered at La Cygne No. 1, statistical analyses as described in the following sections were not performed.

In addition to the data from EPA monitoring sites, data acquired from the Wellman-Lord demonstration unit at Northern Indiana Power Service Company's (NIPSCO) D. H. Mitchell No. 11 generating unit, Gary, Indiana, were also included in the statistical analyses which follow. A description of the Wellman-Lord process and its installation at the Mitchell plant may be found in the proceedings: Symposium on Flue Gas Desulfurization, Hollywood, Florida, November, 1977, EPA-60017-78-058, Page 650.

For brevity the test sites are identified in the following sections as follows:

Test Site	Identifier
Cane Run No. 4, LGE	Louisville
Bruce Mansfield No. 1, PPC	Pittsburgh
Eddystone No. 1, PE	Philadelphia
Mitchell No. 11, NIPSCO	Chicago

C. UNUSABLE DATA

Normally the SO_2 monitoring system is not operated when the boiler is down, this time being used for repair, maintenance, and calibration of instruments. During periods when the scrubber is by-passed, the SO_2 monitors at all EPA test sites remained in service. These data, along with data obtained while the scrubber was starting up, not having achieved normal operation, were not included in the data analyzed for this report. However, data was not deleted due to process upsets unrelated to start-ups or shut-downs. All other unused data for the purposes of this report were due to the monitoring system, resulting from outright failures, repair, or routine calibration and maintenance. At the Louisville test site, some data were pre-empted by performance testing of the monitoring equipment.

Table III-1 illustrates the population of unusable data at two test sites by category. As shown, monitoring system problems and repairs accounted for about one-half of unusable data at the Louisville and Pittsburgh test sites. Boiler failures accounted for roughly 25 percent of non-data periods, while monitoring system maintenance accounted for less than 5 percent. Monitoring failures, calibration, and maintenance accounted for 31 and 20 percent of operating time for the two modules at the Louisville site, and nearly 44 percent at the Pittsburgh site. The apparently poor availability of the monitoring systems is not indicative of the state-of-the-art of SO_2 monitoring systems. The shortcomings of these particular systems were discussed in detail earlier in this report.

D. USABLE DATA AND STATISTICAL ANALYSES

The remaining valid data was statistically analyzed according to the ground rules described earlier in this chapter, for the

Table III-1. CATEGORIZATION OF DATA

	Sites		
	Louisville		Pittsburgh
	Module "A"	Module "B"	
Usable Data Points	7582	9414	3890
Unusable Data:			
Boiler down	1444	1444	1245
Scrubber down	414	414	---
Start-up	54	54	---
Monitor failure/repair	3851	2019	2646
Calibration/maintenance	165	165	372
Initial performance test	876	876	---
Unaccounted losses	466	466	---
	14852	14852	8153

following variables as a function of 24-hour averaging time, assuming all data were normally distributed:

- mean
- standard deviation
- average deviation
- percent standard deviation
- SO_2 removal efficiencies

Subsequent analyses showed, in fact, that all data were log-normally distributed. The inlet data findings differed from previous coal sampling studies where coal sulfur data were normally distributed.

Figures III-3 and III-4 show inlet SO_2 data from the Louisville site plotted on normal and log-normal probability paper, respectively, for the period July 23 - December 15, 1977. Data after December 15 resulted from a different coal feed and were deleted to make the statistics valid. Apparently, the best fit was the plot of inlet SO_2 values against log probability of occurrence (Figure III-4). From this plot the mean value of SO_2 inlet emission rate was 5.75 lb/MBTU and the geometric mean 1.08 lb/MBTU.*

Data from the remaining sites were also plotted in Figure III-4. Table III-2 summarizes the results. Mean inlet SO_2 values ranged from 5.12 to 6.30 lb/MBTU with geometric standard deviation from 1.07 to 1.12 lb/MBTU.

Figures III-5 and III-6 show the outlet SO_2 data from the Louisville site as functions of normal and log-normal probability. Again, the best fit appears to be log-normal probability. Mean

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*The mean is y-intercept at 50 percent value; geometric standard deviation is the ratio of the 93.3 percent and 6.7 percent less than values, raised to the 1/3 power.

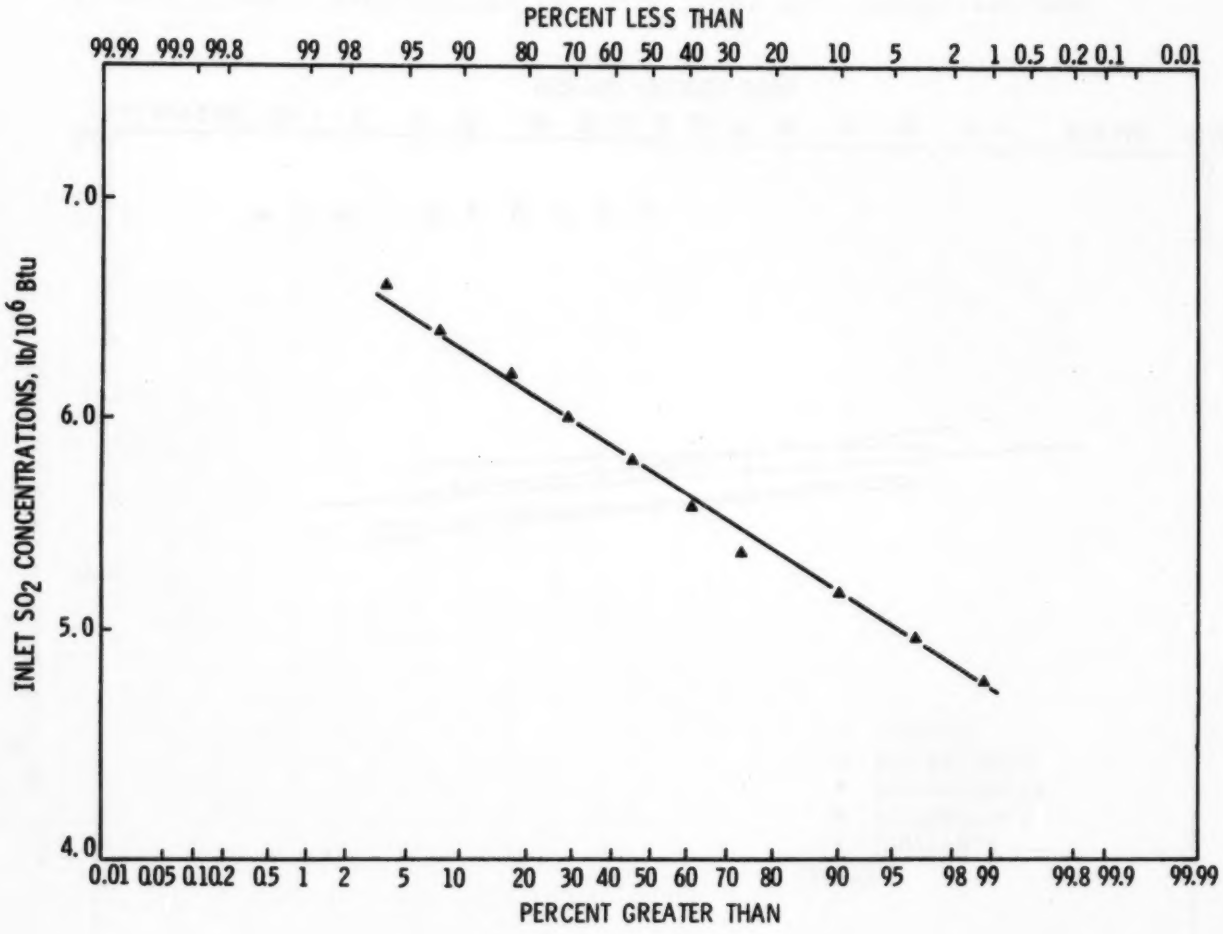

Figure III-3. Probability Vs. Linear Inlet SO_2 Concentrations from Louisville Site

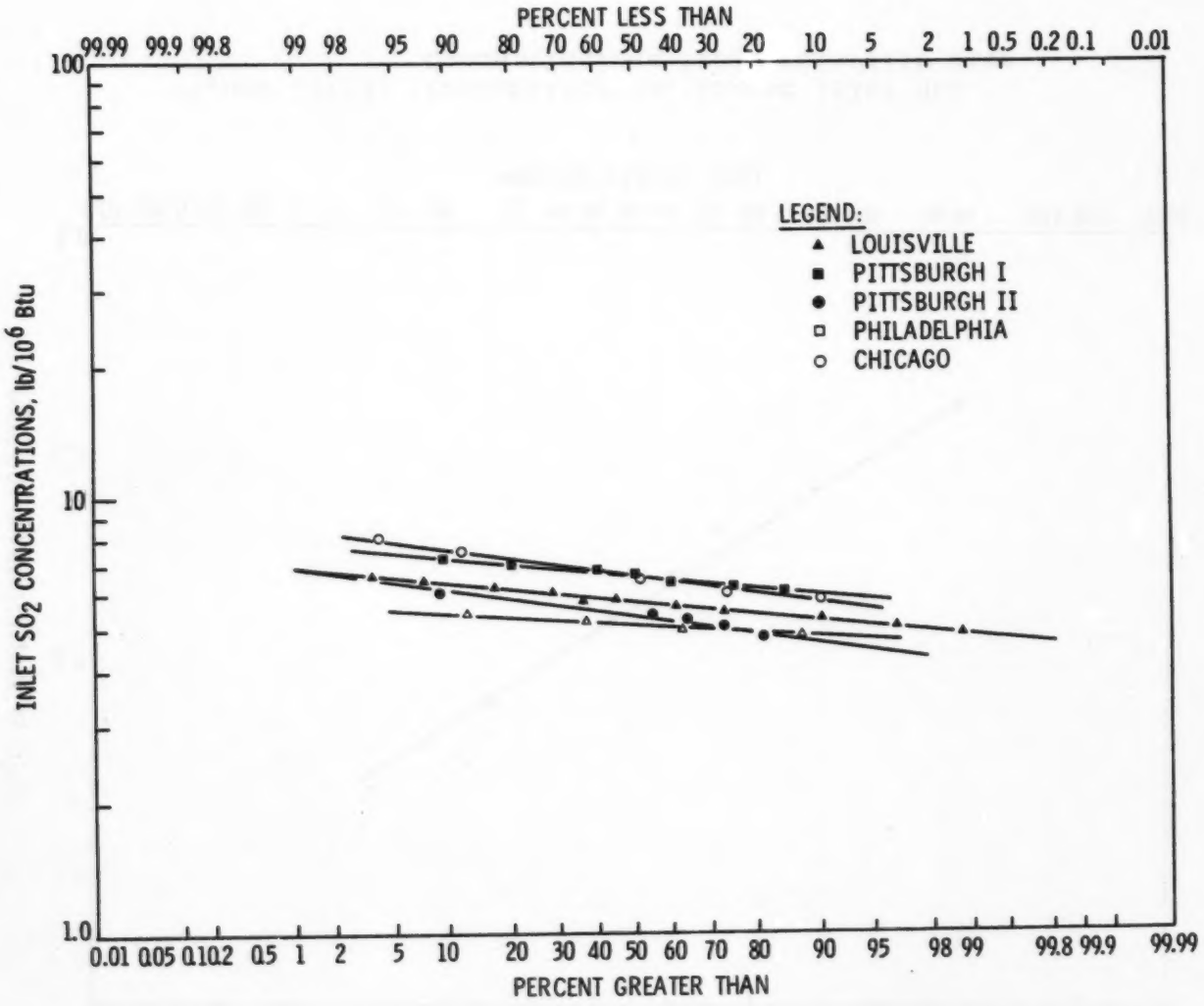
PERCENT LESS THAN
99.99 99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
100
10
1.0
INLET SO_2 CONCENTRATIONS, lb/10^6 Btu
LEGEND:
LOUISVILLE
PITTSBURGH I
PITTSBURGH II
PHILADELPHIA
CHICAGO
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99
PERCENT GREATER THAN

Figure III-4. Probability Vs. Log Inlet SO_2 Concentrations

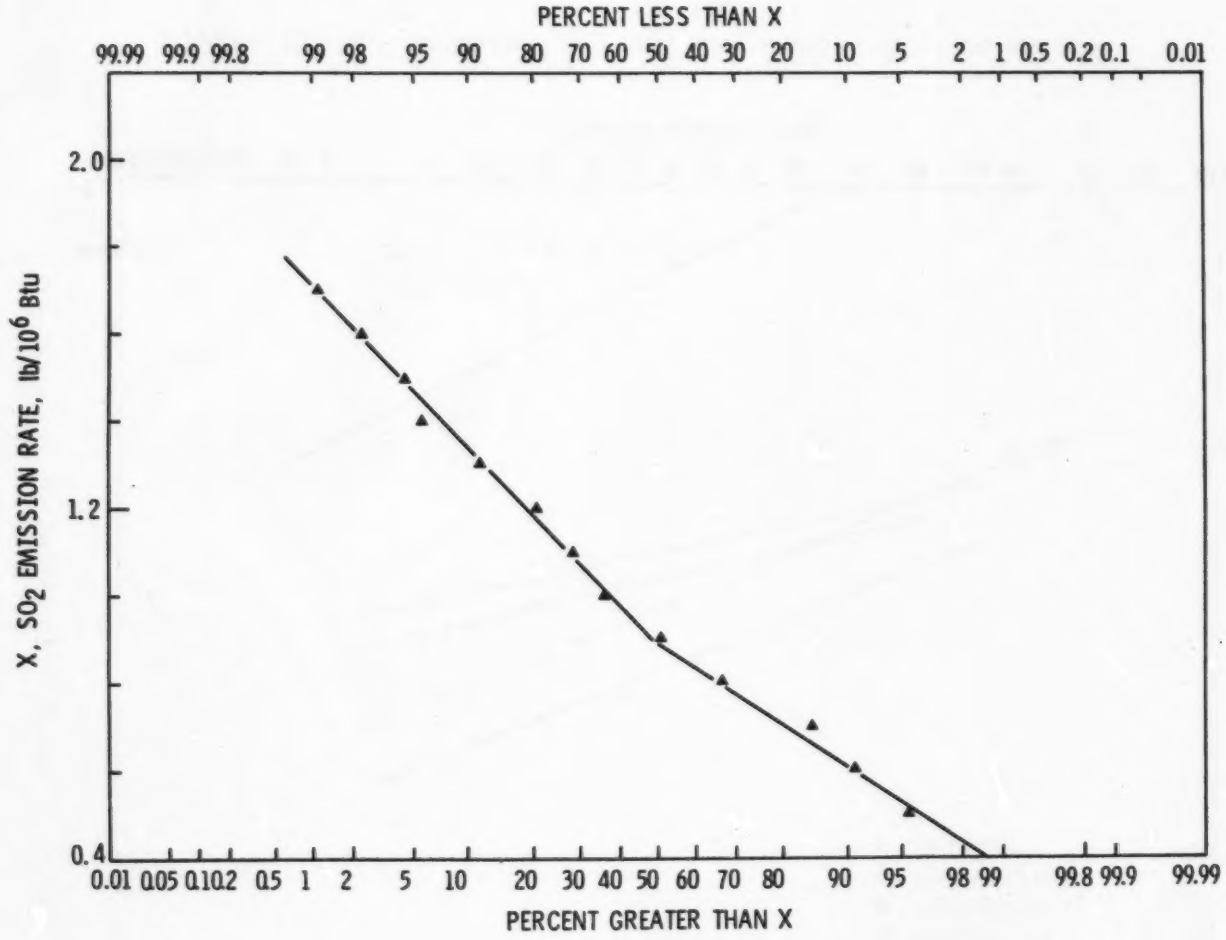

Figure III-5. Probability Vs. Linear Outlet SO_2 Emissions from Louisville Site

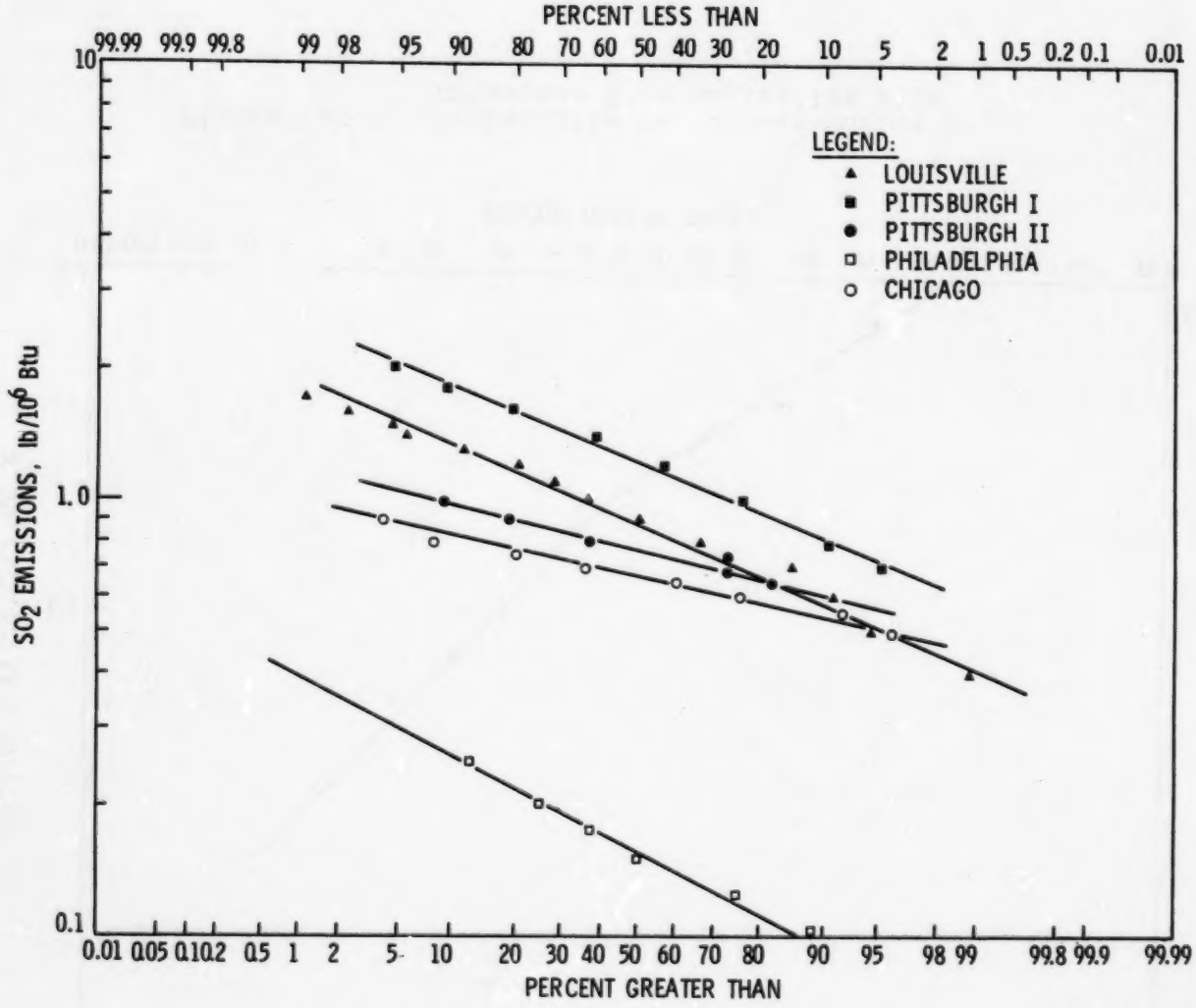
PERCENT LESS THAN
99.99 99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
10
1.0
0.1
LEGEND:
LOUISVILLE
PITTSBURGH I
PITTSBURGH II
PHILADELPHIA
CHICAGO
SO2 EMISSIONS, lb/10^6 Btu
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99
PERCENT GREATER THAN

Figure III-6. Probability Vs. Log Outlet SO_2 Emissions

Table III-2. INLET SO_2 EMISSIONS
(24-hr. Averaging Period)

SITE	NO. OF POINTS	MEAN INLET SO_2 $lb/10^6$ BTU	GEOMETRIC STANDARD DEVIATION $lb/10^6$ BTU
Louisville	82	5.75	1.08
Pittsburgh No. 1	20	6.30	1.07
Pittsburgh No. 2	11	5.40	1.11
Philadelphia	8	5.10	1.05
Chicago	25	6.30	1.12

and geometric standard deviations were graphically determined to be 0.89 and 1.35 lb/MBTU respectively.

The remaining SO_2 emission data for four other test sites were plotted (Figure III-6) on log-normal probability paper. All five sites exhibited a reasonably good data fit. Results of graphical analyses are tabulated in Table III-3.

Pittsburgh I and II data represent the two periods of operation - Period I when pH control was a severe problem and Period II when pH control was improved.

Table III-3 shows the geometric standard deviation of outlet emissions to vary from 1.2 to 1.5.

Since both the inlet and outlet SO_2 levels were judged to be log-normally distributed, it was assumed that the performance of each scrubber system, expressed as a percentage SO_2 reduction

$$\left[100\ \frac{(1\text{-outlet})}{\text{inlet}}\right]$$

would also be log-normally distributed. Figure III-7 shows a plot of SO_2 reduction versus log-normal probability. In the range (70 to 98 percent removal) shown, the straight line relationships of data and subsequent graphical analysis are prone to greater error. Therefore, a better plot is one which transforms the data to the more favorable area on the logarithmic chart, i.e., the 1 to 4 range.

Such a transform is 100-(SO_2 removal, percent) which in reality is outlet/inlet x 100 or percent SO_2 remaining. When plotted as shown, in Figure III-8, the straight line fits allow much better graphical interpretation of data. Table III-4 shows the results

Table III-3. OUTLET SO_2 STATISTICS
(24-hr. Averaging Period)

SITE	NO. OF POINTS	MEAN OUTLET SO_2 $lb/10^6$ BTU	GEOMETRIC STANDARD DEVIATION $lb/10^6$ BTU
Louisville	89	0.88	1.38
Pittsburgh No. 1	20	1.21	1.37
Pittsburgh No. 2	11	0.77	1.21
Philadelphia	8	0.155	1.48
Chicago	25	0.67	1.19

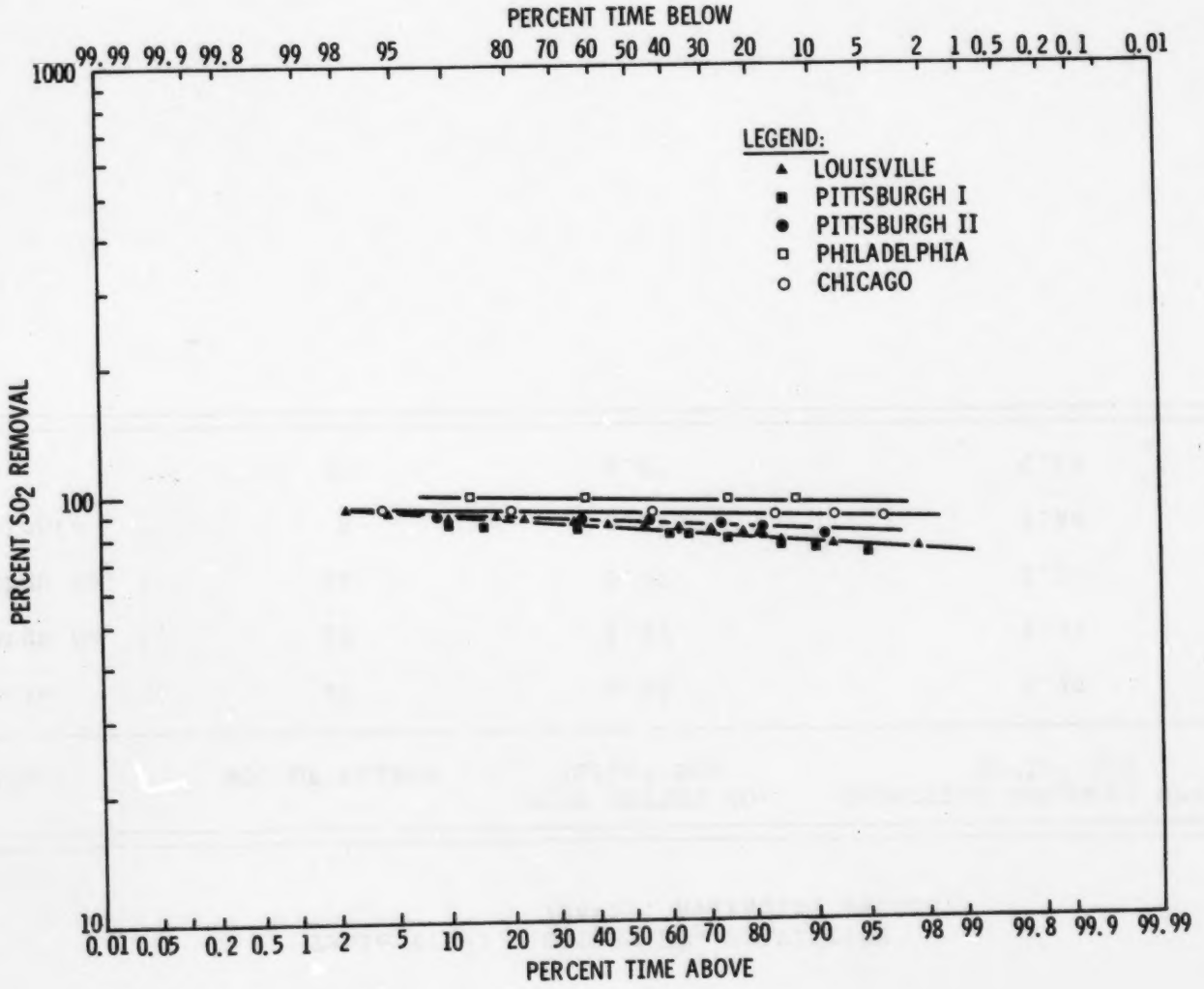
PERCENT TIME BELOW
99.99 99.9 99.8 99 98 95 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
1000
100
10
PERCENT SO_2 REMOVAL
LEGEND:
LOUISVILLE
PITTSBURGH I
PITTSBURGH II
PHILADELPHIA
CHICAGO
0.01 0.05 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99
PERCENT TIME ABOVE

Figure III-7. Probability Vs. Percent SO_2 Removal

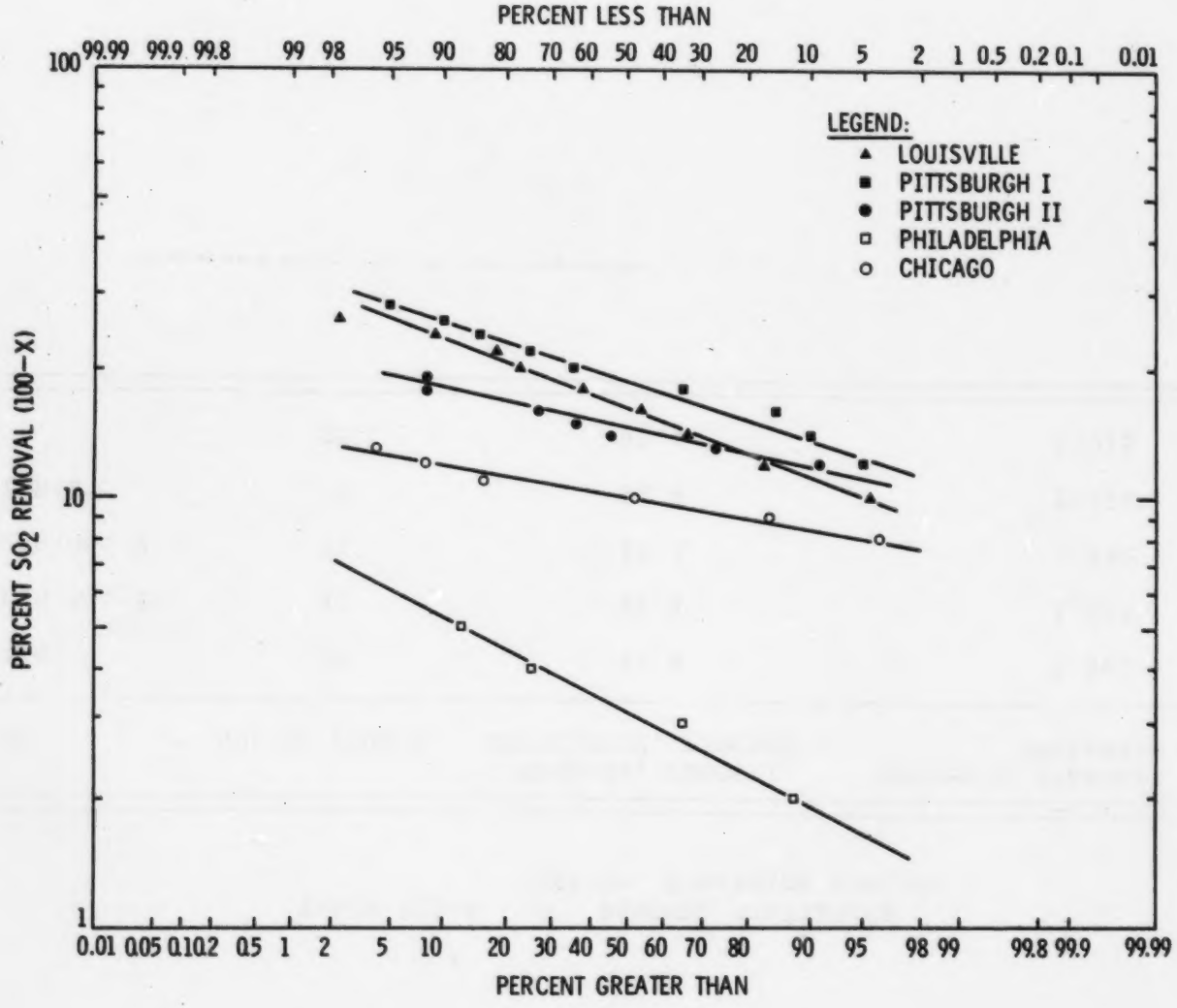
PERCENT LESS THAN
99.99 99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.01
100
10
1
PERCENT SO_2 REMOVAL (100−X)
LEGEND:
LOUISVILLE
PITTSBURGH I
PITTSBURGH II
PHILADELPHIA
CHICAGO
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99
PERCENT GREATER THAN

Figure III-8. Probability Vs. 100 Minus Percent SO_2 Removal

Table III-4. SO_2 REMOVAL STATISTICS
(24-hr. Averaging Period)

SITE	NO. OF POINTS	MEAN SO_2 REMOVAL EFFICIENCY, PERCENT	GEOMETRIC STANDARD PERCENT DEVIATION
Louisville	89	83.8	1.060
Pittsburgh No. 1	20	81.4	1.057
Pittsburgh No. 2	11	85.3	1.029
Philadelphia	8	96.8	1.014
Chicago	25	90.0	1.015

of these graphical interpretations. The means (converted back to percent removal) ranged from 81.4 to 96.8, while geometric standard deviations ranged from 1.014 to 1.060.

Some questions exist regarding the "dampening" of inlet sulfur variations by flue gas scrubbing. Though many parameters enter into the design of FGD systems, the reactivity of the system chemistry and the degree of process control play an important role in dampening of SO_2 emissions as well as the amount of excess reactant present.

In all the systems monitored, process controls for maintaining the desired reactant concentrations (measured by pH) were usually operated in the manual rather than the automatic mode.

Using the values for the mean and geometric standard deviation from Tables III-2 and III-3, the variations in SO_2 concentration were compared for several confidence levels as shown in Table III-5. The dampening effect is measured by comparing inlet variation to outlet variation and is calculated as shown in the table.

Since each system is operated under a different set of conditions, e.g., coal fired, boiler loading, type of scrubber module, excess reactant, few conclusions can be drawn. It is noteworthy, however, that a negative dampening is observed for the first batch of Pittsburgh data where pH control was very poor and that a 70 percent dampening resulted when pH control improved. The more reactive sodium, magnesium oxide, and magnesium oxide enriched lime systems showed considerably more dampening than the lime system alone, as would be expected under comparable operating conditions.

Table III-5 can be used to illustrate the impact of a "never to be exceeded" regulation where scrubbers are the control of choice.

Table III-5. VARIATION IN SO_2 CONCENTRATIONS IN LB/10^6 BTU (24-hour averages)

	Confidence Level		
	68.7%	95%	99.7%
Louisville:			
Inlet	±0.46	±0.96	±1.49
Outlet	±0.33	±0.80	±1.43
Percent Dampening[1]	28.2	15.7	4.0
Pittsburgh:			
#1 Inlet	±0.44	±0.91	±1.42
Outlet	±0.45	±1.07	±1.92
Percent Dampening	-0.0	-17.5	-35.2
#2 Inlet	±0.59	±1.25	±1.99
Outlet	±0.16	±0.36	±0.59
Percent Dampening	72.9	71.2	70.4
Philadelphia:			
Inlet	±0.26	±0.52	±0.80
Outlet	±0.07	±0.18	±0.35
Percent Dampening	70.8	64.7	56.8
Chicago:			
Inlet	±0.76	±1.60	±2.55
Outlet	±0.13	±0.28	±0.46
Percent Dampening	82.9	82.5	82.0

[1]Percent Dampening = $\frac{\text{inlet - outlet}}{\text{inlet}} \times 100$

At the 99.7 percent confidence level the variation in SO_2 emissions is rather large in comparison to the present standard for new coal-fired boilers above 250 MBTU/hr - 1.2 lb SO_2 per MBTU input. The best system examined has a ± 0.35 lb/MBTU variation on a 24-hour basis, implying that a lifetime mean of 0.85 lb/MBTU SO_2 emissions would be required in order to comply 99.85 percent of the time. The lime system with a ± 1.43 lb SO_2/MBTU expectancy could not always comply, and would have to average 0.40 lb SO_2/MBTU over its lifetime to be in compliance 97.5 out of every 100 24-hour periods or roughly 356 days per year.

Finally, the effects of longer averaging periods upon performance were examined. Since insufficient data exists for a rigorous examination, only the Louisville system was considered at 7 and 14-day periods. Figure III-9 and Table III-6 summarize the findings. The differences in mean values are due to more data points used in the 24-hour case (89) versus 84 24-hour points in the 7 and 14-day cases.

As expected, the geometric standard deviation decreases with increased averaging time, increasing the confidence of compliance with a given emission standard or percentage removal requirement.

Table III-6. CUMULATIVE LOUISVILLE STATISTICS VS. AVERAGING TIME

Percent Recovery	Averaging Period 24-hour	7 days	14 days
No. of Periods	89	12	6
Geometric Mean	83.8	83.1	83.1
Geometric STD Deviation	1.06	1.05	1.03
SO_2 Emissions, lb/10^6 BTU:			
No. of Periods	89	12	6
Geometric Mean	0.88	0.95	0.95
Geometric STD Deviation	1.38	1.26	1.17

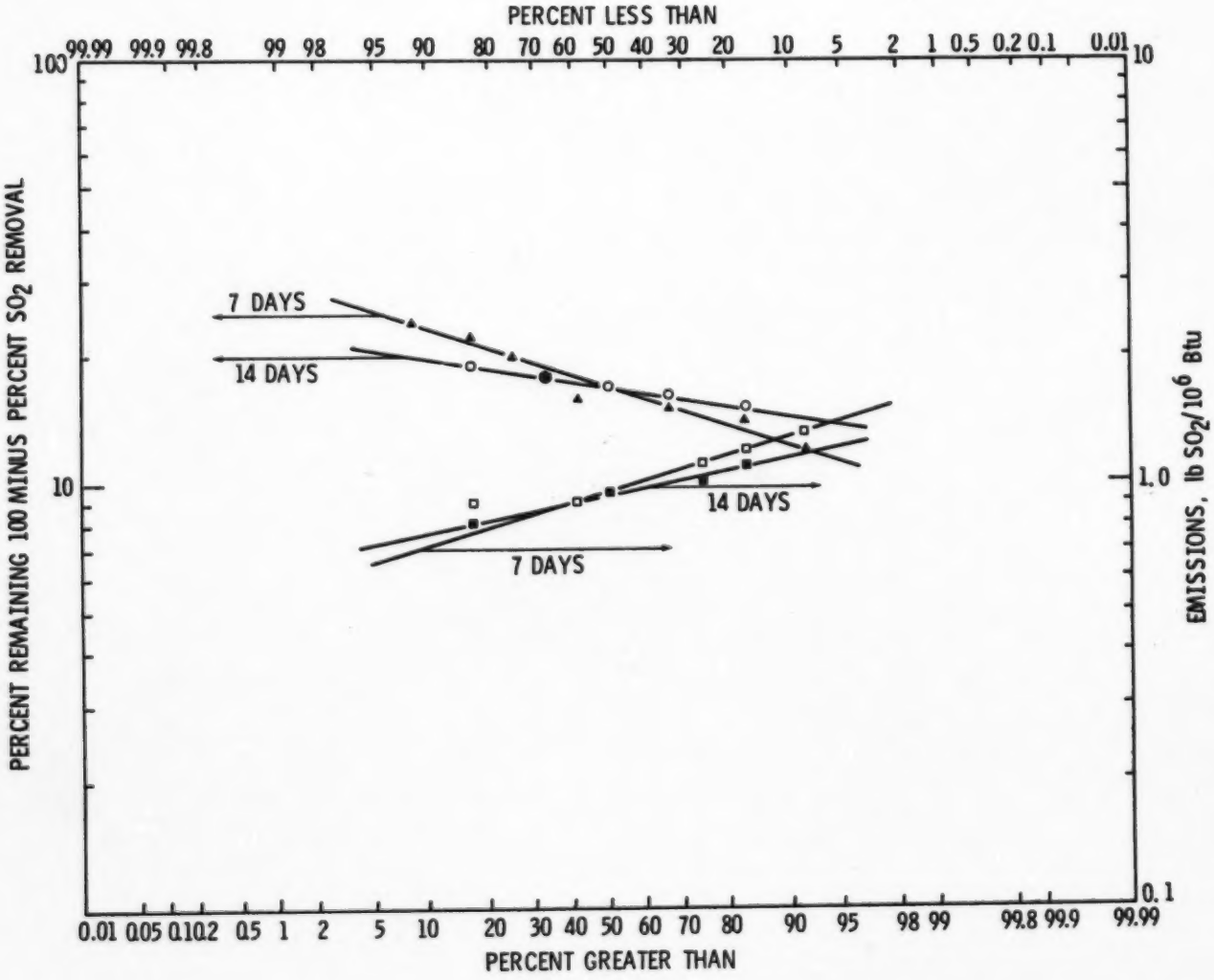

Figure III-9. Louisville Data for 7 and 14 Day Averaging Periods

IV. RECOMMENDATIONS AND CONCLUSIONS

A. Although the availability of the monitoring systems during the first four months of EPA's study ranged from 56 to 80 percent, most problems were a result of the system design.

B. The oxygen monitoring instrumentation is the least reliable piece of equipment in the SO_2 monitoring system used for this study. Oxygen data by Orsat analysis or a suitable backup system may be necessary on occasions.

C. Research was necessary to define the expected sample conditions with respect to moisture content, and to develop the most acceptable procedure for moisture measurement or estimation.

D. Manual data acquisition and reduction has required a very high manpower investment. It is recommended that automatic data systems to acquire the individual instrument outputs and convert to units of the standard, averaged over the specified intervals, be used for routine monitoring.

E. SO_2 scrubbers do have a dampening effect upon inlet SO_2 variations over longer 24 hour or greater averaging periods. The instantaneous dampening effect is masked by short-term variations in scrubber performance due to system response lags. Dampening of 70 to 80 percent, as calculated by outlet standard deviation divided by inlet standard deviation, has been shown in these tests on a 24-hour basis.

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F. Longer averaging periods have the effect of lowering the variance of scrubber performance as measured by SO_2 removal efficiency and outlet SO_2 emissions.